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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

STRATEGIES IN THE TOPOLOGICAL APPROACH TO
ELECTROMAGNETIC INTERFERENCE CONTROL

by

Vernon D. Ingram

December 1987

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The ability of standard commercial equipment cabinets to be used to provide a electromagnetic interference is explored. The internal to external, and external to internal, electromagnetic isolation provided by various configurations of cabinet-penetrating conductors was measured at frequencies from 20 HZ to 20 MHZ. Excellent isolation was obtained over the entire frequency range when penetrating conductors (coaxial cables, grounds buses, power conductor green-wires, and power conductor black and white wires) were installed in accord with barrier principles. Little or no isolation was obtained with the direct penetration of the cabinet by conductors. These results were confirmed by laboratory and field measurements (at operating CDAA sites).

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Strategies In The Topological Approach To Electromagnetic Interference Control

by

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Lieutenant, United States Navy
B.S.E.E., University Of Washington, 1980

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

ABSTRACT

The ability of standard commercial equipment cabinets to be used to provide a barrier to electromagnetic interference is explored. The internal to external, and external to internal, electromagnetic isolation provided by various configurations of cabinet-penetrating conductors was measured at frequencies from 20 HZ to 20 MHZ. Excellent isolation was obtained over the entire frequency range when penetrating conductors (coaxial cables, grounds buses, power conductor green-wires, and power conductor black and white wires) were installed in accord with barrier principles. Little or no isolation was obtained with the direct penetration of the cabinet by conductors. These results were confirmed by laboratory and field measurements (at operating CDAA sites).

TABLE OF CONTENTS

TABLE OF TERMS AND ABBREVIATIONS

BNC .... Bayonet type RF connector.

Bullseye site.. Receiver outstation and member of High Frequency Direction Finding Network.

Corona Noise... RFI caused by a breakdown across Inter-electrode space resulting in either a spark or glow discharge at atmospheric pressure.

EMC............ Electromagnetic Compatibility.

EMI............ Electromagnetic Interference.

FFT............ Fast Fourier Transform.

Gap Noise...... RFI caused by microspark breakdown across small gaps on transmission and distribution lines.

HFDF........... High Frequency Direction Finding.

ISM Noise...... Noise caused by out of band Industrial, Scientific and Medical machine devices.

Micro-cap II... Student Version 3.7 of Micro-cap Circuit Design program.

NEC............ National Electrical Code.

NPS............ Naval Postgraduate School Monterey, California.

NSGA........... Naval Security Group Activity.

RFD............ Radio Frequency Distribution.

SPAWARS........ Naval Space and Warfare Systems Command.

TEMPEST........ The unclassified name referring to investigations and studies of compromising emanations.

Topological.... Closed Surface approach to Electomagnetic Interference Control.

Triplen........ Harmonic currents on neutral and ground AC wires.

Ullman Room.... Receiver collection room at Sabana Seca, PR.

ACKNOWLEDGEMENT

I thank all who have helped me with my research and Site studies. I particularly thank Professor Jauregui and Professor W. Ray Vincent for their patience, faith and encouragement. Finally I thank my wife Joyce for the love, understanding, and support she gave me.

I. INTRODUCTION

Electromagnetic interference (EMI) limits the ability of a receiver to detect desired signals. A signal from a distant transmitter may be distorted by interference to such an extent that the original information in the signal is partially or completely lost.

Over the last several years considerable research has been done in electromagnetic interference at Bullseye HFDF sites. This work has been mainly aimed at reducing the noise levels at these sites to enhance the signal to noise ratio. Recent surveys indicate that noise caused by both external and internal sources continues to degrade site performance. There is a general lack of information about noise reduction, and personnel at most sites do not recognize the significance of their noise problem or its significant negative effect on their mission. These site surveys have identified many internal and external noise sources, and a number of site vulnerabilities.

Solutions to EMI are becoming more complex with the rapidly expanding use of radio systems. Electronic systems are often purchased and installed without proper consideration of electromagnetic compatibility (EMC). For example, the mixture of digital and analog equipment in

receiving sites often results in the need to consider both external and internal sources of interference.

The control of EMI at the cabinet level is explored in this thesis. Chapter Two examines ways to reduce interference and covers the experimental set-up, test procedures and instrumentation techniques. Chapter Three continues the experimental work of Grodek [1] on noise sources and penetrating conductors and identifies the experimental results and procedures carried out on a typical equipment cabinet in regard to reduction of green-wire currents and penetrating conductors. Chapter Four includes the results of recent site surveys, specifically in the control of green-wire currents. Chapter Five concludes with a discussion of the benefits, concerns and recommendations reached from the laboratory and field work.

The primary purpose of this thesis is to understand how to treat penetrating conductors that supply AC power to the electrical equipment installed in cabinets, and to show how noise is coupled in and out of standard equipment cabinets.

II. BACKGROUND

A. INTRODUCTION

Over the years, the U.S. Navy Bullseye HFDF sites have been modernized and upgraded according to perceived needs and technological advances. Many of these operational changes have also created a system that is considerably more susceptible to electromagnetic interference of various types [1-4]. This interference has a significant effect on system performance and therefore, on site effectiveness.

Early site surveys done by the Signal-To-Noise-Enhancement Teams (SNEP teams), comprised of NPS students, staff and contractors, identified many EMI sources at Bullseye sites and found how these unwanted signals can be coupled into the receiver paths. Studies by O'Dwyer [4] and 9Grodek [1] have provided considerable practical guidance in the area of noise reduction and noise source coupling.

B. APPROACHES

Different approaches have been considered over the years in an effort to reduce the effect of noise as an interference signal. These include: 1.) Trying to suppress the noise at its source, 2.) making the receiver less sensitive to the interference source and 3.) placing a

"break" in the path between the noise source and the receiver.

Field results have proven that eliminating noise at its source can be done when tackling most external site noise sources. For example, SNEP team members have successfully coordinated with local power companies to locate powerline interference sources such as gap discharge and corona powerline sources. Out of band Industrial, Scientific, and Medical (ISM) noise sources have also been tracked down and reduced during site visits. External noise sources are often very difficult to track down and correct, but this process effectively reduces noise levels in site receivers.

The team also identified many noise sources internal to sites. Most of these are identified as sources associated with mission oriented equipment, and can not always easily be eliminated.

While technology has improved a receiver's ability to reject noise and still receive low-amplitude signals, noise injected into the RF-distribution path still degrades the performance of receivers. The approach that has proven to be the most successful at reducing the noise at the receiver input from internal sources is to place a "break" or barrier between the noise source and susceptible equipment. A "topological barrier" around the affected system would be the ideal way to control the interference

signal. However, from a practical point of view this is difficult because signal, power, and ground conductors must enter and leave the equipment.

C. GENERAL APPROACH ON EXPERIMENTATION

In-house data was collected using a standard steel equipment cabinet, enclosed on its sides, and with a louvered back door and top. This equipment cabinet, shown in Figure 1, is typical of one that would be found in a RF Distribution (RFD) room at a Bullseye site. The cabinet was modified by removing the power panel and installing two versions of green-wire barrier plates. The louvered top was removed, the painted surface of the cabinet was burnished to form a metal to metal bond with test barrier plates, and the barrier plates were installed. An aluminum panel was used to completely enclose the top portion of the equipment cabinet. The ventilation fan located at the bottom of the bay was not removed. An AC power strip was installed in the cabinet interior to provide convenient internal power. A 1.5" x .25" x 54" copper bar was mounted along the back right side frame of the cabinet to provide a ground bus that was both mechanically and electrically connected to the inside surface of the cabinet. Cabinet power was supplied by a standard three conductor AC power cord that plugs into the wall socket at one end and was connected to one, or the other, green-wire barrier plates at the top of the cabinet.

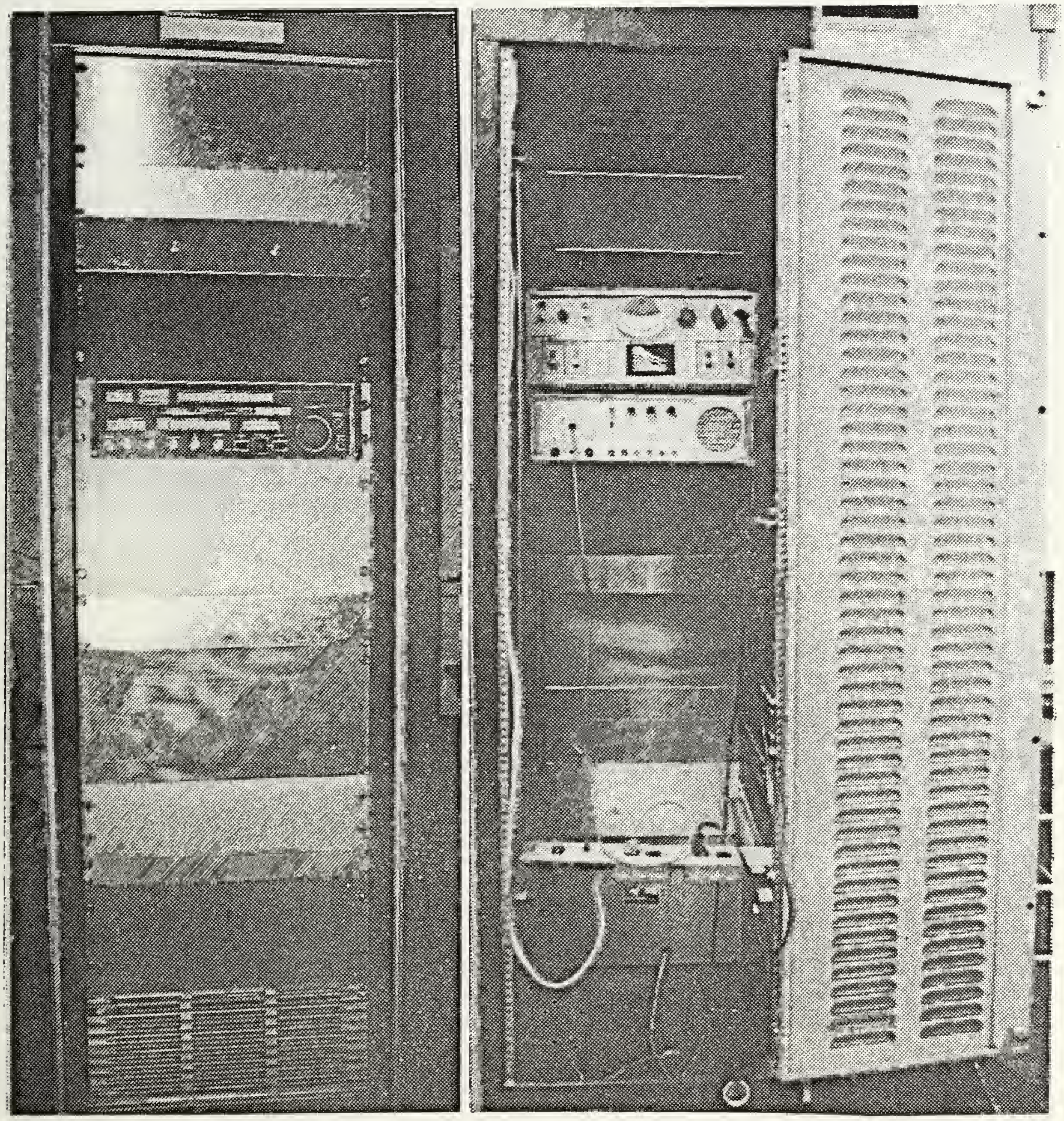
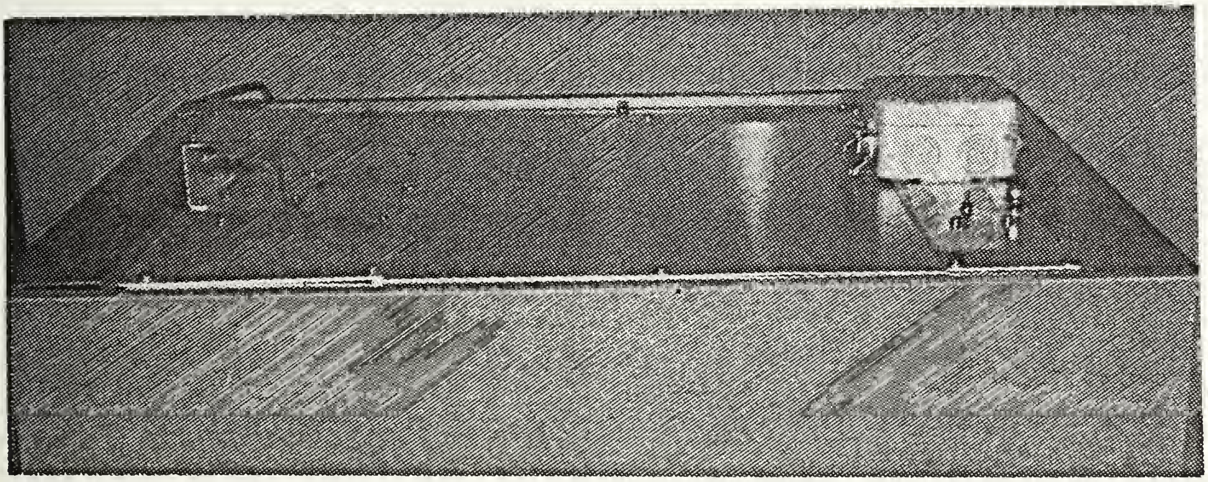


Figure 1. Front and Back View of Experimental Cabinet

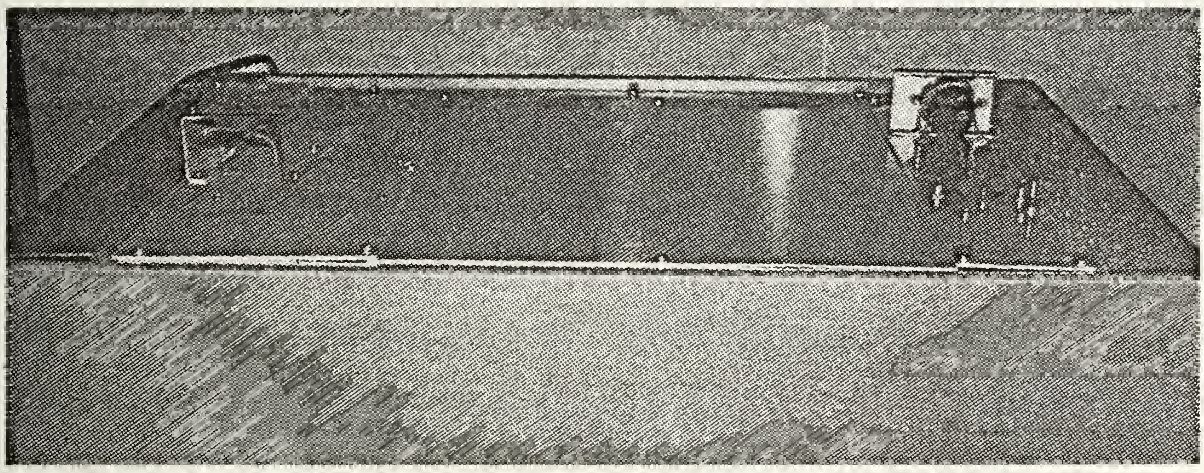
An HF receiver (Model WJ-8888) was installed in the front panel of the rack to provide power loading, along with the ventilation fan for the green-wire current test. The cabinet was on an insulated deck throughout the experimentation. During penetrating conductor experiments, the front of the cabinet was completely enclosed using aluminum panels that were tightly butted together and tightly bonded to the cabinet by machine screws. This is much like an equipment bay would be configured at a receiver site. Although this cabinet was modified for experimentation, and a verification was done for continuity on all rack surfaces, it is none the less still considered to be a typical commercial cabinet, i.e., without welded seams or RF gaskets. This cabinet, as installed in most RFD's, does not provide the EMI/RFI suppression obtained with a TEMPEST approved installation.

D. GREEN-WIRE BARRIER PLATE

The green-wire barrier plates were mounted as shown in Figure 2 on the top of the equipment cabinet. This configuration, either front or back mounting, is similar to those installed at most sites, except for the top location. (All site installed barrier plates have been mounted on the bottom of the cabinet because power was supplied from under floor conductors.) The top mounting was chosen because it allowed the most freedom of access during experimentation



New and older Barrier Plates



New and Test Filter mounted Barrier Plates

Figure 2. Green Wire Barrier Plates Mounted on Experimental Cabinet

without changing the cabinet position, and would more than likely be the position for the green wire barrier kit on a newly installed cabinet with power in an overhead trough feed.

The barrier kit, located in the top front of the cabinet, is the most recent design. This kit, constructed of aluminum with iridite coating, is the same as that installed by SNEP teams at Navy HFDF sites. Typical site modification includes complete removal of cabinet external AC outlets and removal of all paint in mounting area. AC power is normally connected through flexible conduit to the external side of the barrier plate and the green wire is connected to this surface. Black and neutral wires are threaded through a small penetration in the barrier plate to a terminal on the internal surface for distribution to cabinet equipment. A bolt, separate from that used for the external green wire, is used to secure the internal green wire to the internal surface of the barrier plate. From there it is connected to a terminal for internal distribution.

The older kit, located in the rear top, was installed in a few of the first Bullseye sites to undergo SNEP upgrade. It is no longer being installed at sites, and has not been replaced where already installed. Its installation was the same as the newer kit. Its

installation on the experimental cabinet was only to obtain data for comparison purposes.

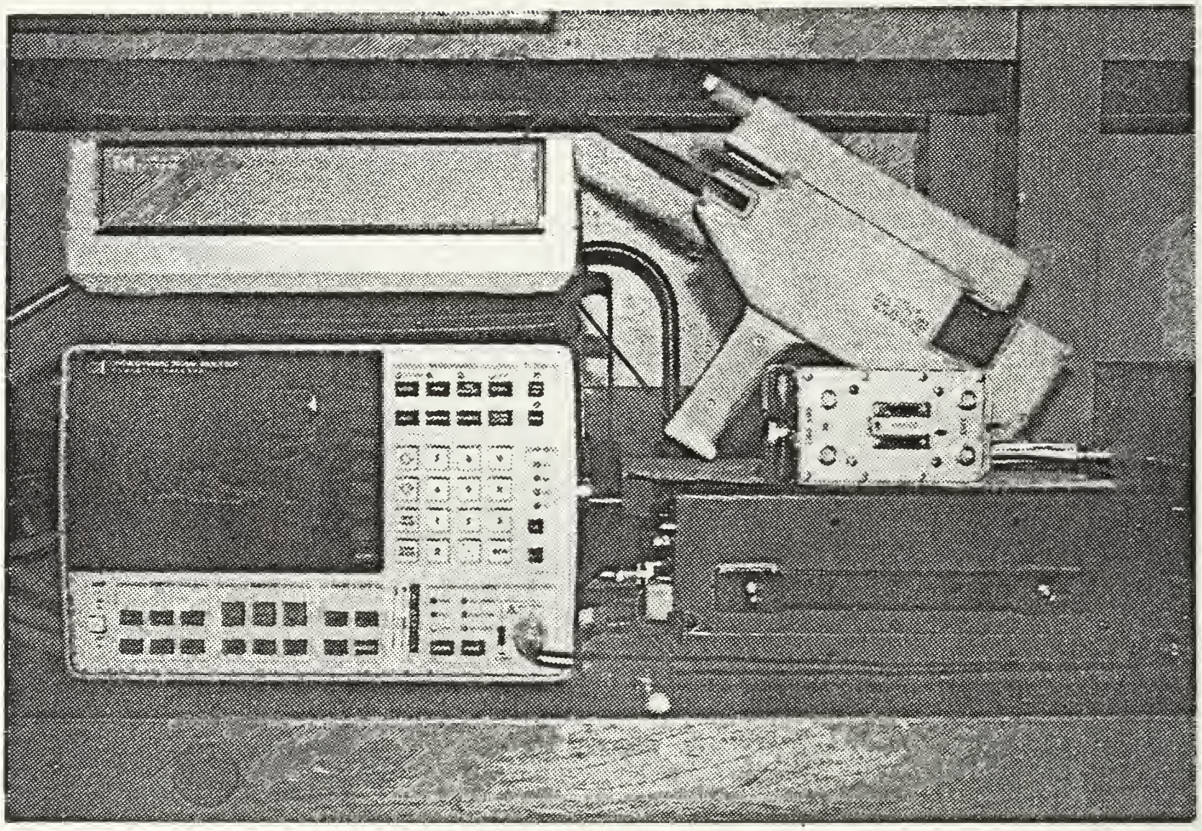
E. LOW FREQUENCY INSTRUMENTATION

The primary components of test set-up used for low-frequency analysis are shown in Figure 3. They are the HP3561A Dynamic Signal Analyzer, Tektronix CT-5 High current Transformer (used in conjunction with the P6021 AC current probe) and a variable gain (40 dB in 10 dB steps) low-frequency line amplifier. As configured for these tests, they provided the ability to accurately measure current in any conductor over the frequency range of 12 Hz to 100 KHz.

The CT-5 is a pistol-grip type current clamp with a frequency range of 12 Hz to 20 MHz when used with the P6021 probe. It has extended range capability for measuring large currents and current sensitivity of 40 mA/mV (2mA/mV P6021 alone).

The low-level signal measurement capability was increased by using a line amplifier. The line amplifier provides adjustable gain in 10 dB steps. To minimize the introduction of stray 60-Hz effects, and harmonics of 60 Hz from power supplies, the line amplifier was battery powered.

The HP-3561A is a single-channel, Fast-Fourier Transform (FFT), signal analyzer that covers the frequency range of 0 to 100 KHz. It provides high dynamic range (80 dB) for analysis of signals and noise of interest. Display



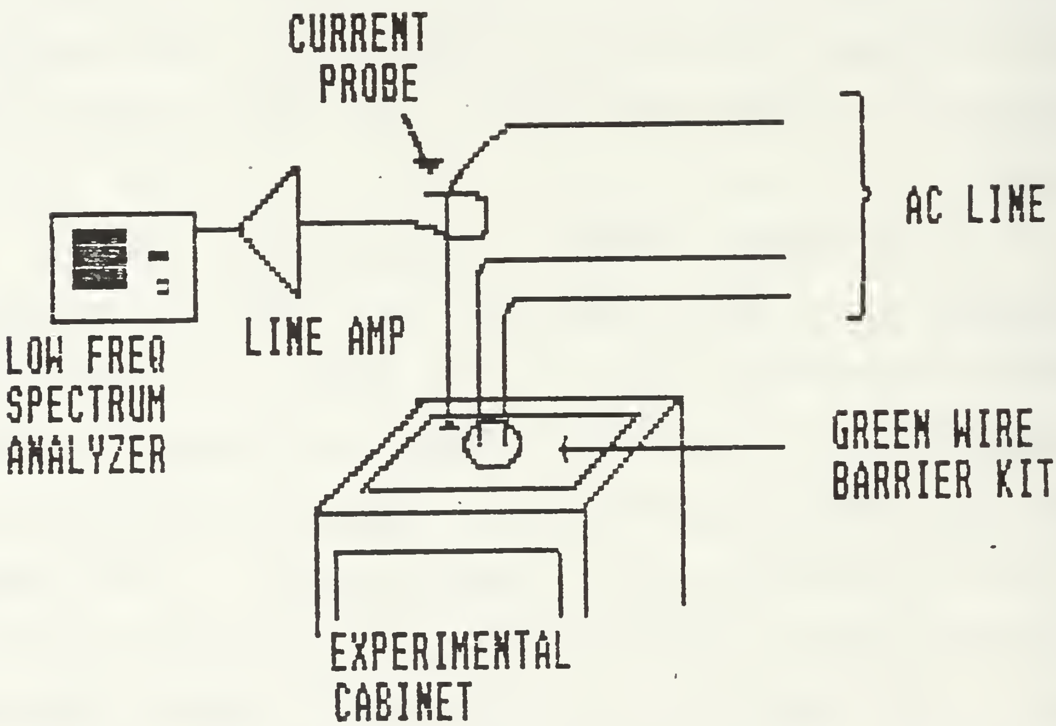


Figure 3. Low Frequency Experimental Instrumentation

formats include single traces, two traces and up to 60 traces in map type format. It can store up to two display traces in non-volatile memory for later recall and analysis. These displays can be either directly plotted or printed using an HP Thinkjet printer.

F. PENETRATING CONDUCTOR PROCEDURES

The test cabinet described earlier was used to test some simple topological controls and to analyze the HF noise problem. Two small penetrations approximately 3/16" in diameter were made in both sides of the cabinet. The paint was removed from both inside and outside surface areas around these holes. For these experiments the front of the cabinet was completely enclosed with panels except for the mounted receiver area and a bottom louvered area used for air circulation. The mounted receiver was not used during these tests and served only to simulate a site configured cabinet.

AC power was supplied via the green-wire barrier and was used as the internal power for the noise generator during that portion of the test when it was located inside the cabinet. BNC bulkhead connectors were mounted on a front panel cover to allow internal connections to the signal under test. (Opening and closing of the cabinet was not done during test.) Double-shielded coaxial cable was

used to connect both internal probe and external measuring devices.

Double-shielded RG223 coaxial cable and #16 gauge copper wire were used as penetrating conductors. The copper wire was configured to verify the test results obtained by Bly and Tonas [5] and to look at some common compromises in barrier integrity for quantitative comparisons. The coaxial cable was tested to observe how noise is conducted into a standard equipment cabinet.

G. HIGH-FREQUENCY INSTRUMENTATION

The primary measuring components of these experiments included the Develco Model 7200B 3-Axis Display, the HP141T Spectrum Analyzer, the CT-5 High Current Transformer and selected RF amplifiers. Figure 4 shows the usual measurement configuration.

The Model 7200B 3-Axis Display provides a unique measuring tool for observing the spectral and temporal relationship of noise and signals. Figure 5 shows an example of stored time history of the analyzer output. This display can be frozen with the present and previous scans, stored in memory, and the stored view can be orientated for best viewing and signal analysis. (As few as four of the 64 continuous scans can be selected and the viewing angle and depth of view changed.) The 3-axis presentation can be photographed for later analysis.

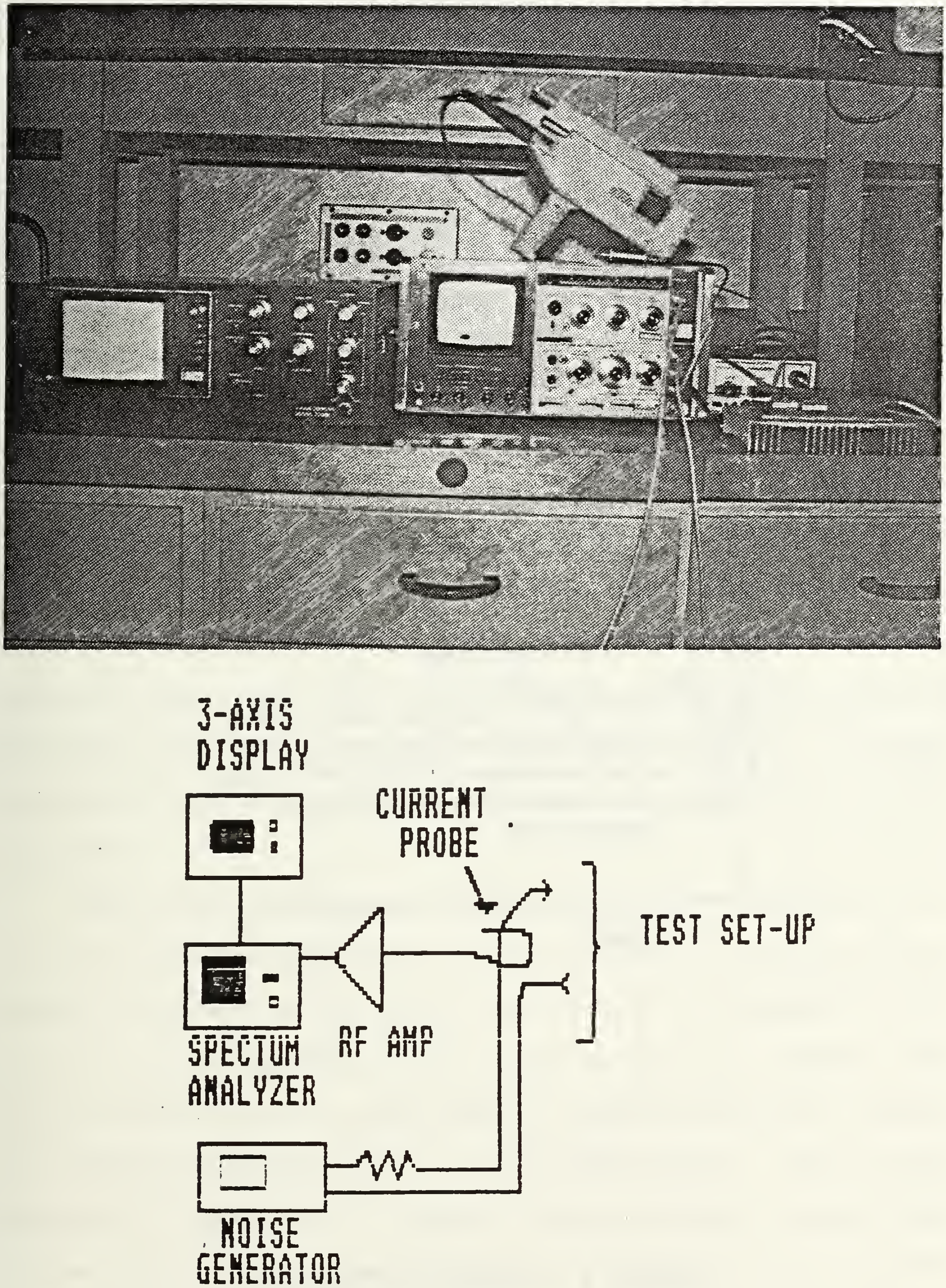


Figure 4. High Frequency Experimental Instrumentation

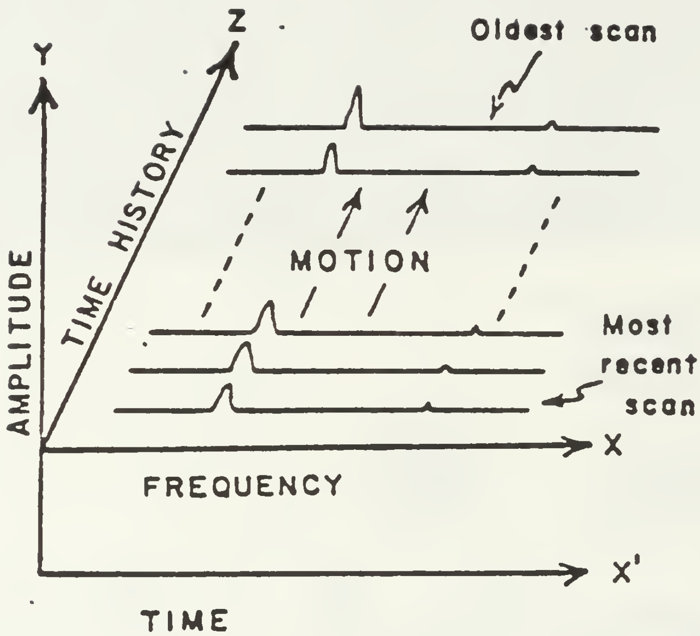


Figure 5. Three Axis Display

The HP141D Spectrum Analyzer is used in conjunction with the 8553B Spectrum Analyzer RF Section and 8552B Spectrum Analyzer IF Section. This configuration allowed observing signals and noise up to 20 MHz, in selectable bandwidths. The RF amplifiers were used singly or in cascade to provide additional gain with a flat frequency response to at least 20 MHz.

H. BARRIER PLATE PROCEDURES

It has been well established that certain measures can improve equipment cabinet barrier effectiveness [4]. These measures, though practical in nature can make the cabinet "effectively impervious to electromagnetic energy" [6]. The barrier plate uses this established topological approach to minimize the level of EMI that can penetrate a standard equipment cabinet by the penetrating conductors that supply AC power.

The primary spectrum content of ground conductors at a site is chiefly between 50 Hz and 8 KHz [7] and is a major path to conduct ground noise in and out of equipment. The barrier-plate experiment uses the AC barrier plates that have been used by the SNEP Team to help minimize the impact of ground conducted noise at Navy HFDF sites. The barrier plates, as described in Chapter Four, basically reduce the noise current conducted between the external and internal green wire. This is done by conducting and confining the

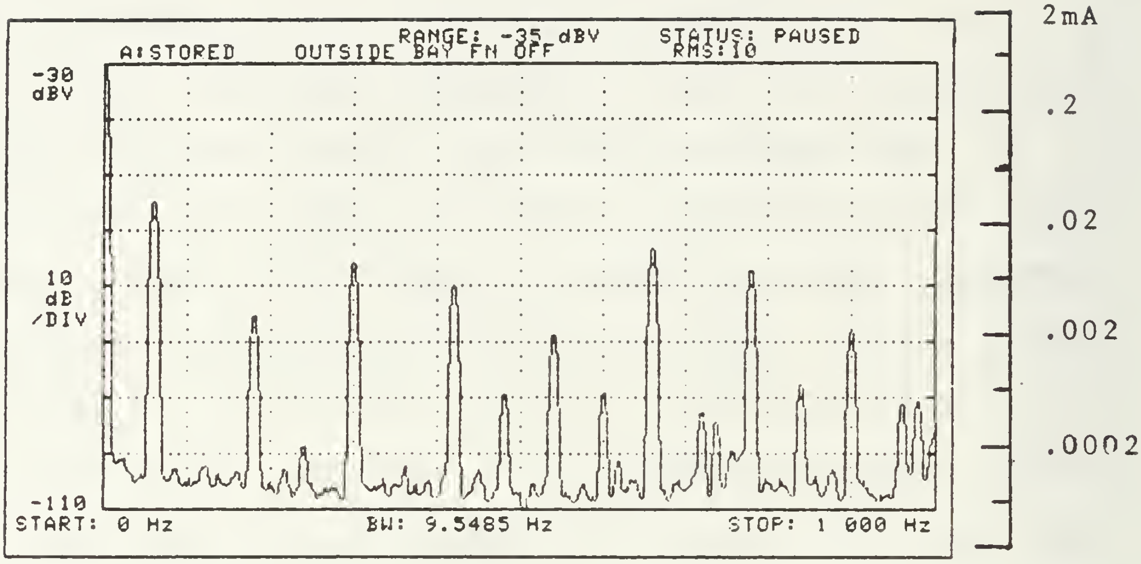
green-wire currents to the surface skin of the cabinet and barrier plates and away from the susceptible equipment.

This skin effect, the penetrated depth in the surface when the injected noise currents decrease by a factor of 0.368 (1/e) varies with frequency. For the 3.2 mm aluminum barrier plate the skin depth varies between 2.67 mm and 0.0084 mm for frequencies from 1 KHz to 1 MHz. Noise current levels on the outside, or inside, are effectively attenuated, creating an isolation barrier to EMI on the green wire.

III. EXPERIMENTATION

A. GREEN-WIRE EXPERIMENT

The experimental procedures and instrumentations discussed earlier provided the data shown in Figures 6 and 7. The measurement parameters for these tests, as well as those for the penetrating conductor tests, are found in the appendix. Figure 6 shows an example of the Signal Analyzer display for the inside and outside green-wire currents when using the barrier plate. The top view (Figure 6a) shows the typical currents flowing in the external ground conductor. Note that both internal and external green wires show the triplen harmonic currents [7] associated with a three phase power source. Figure 6b shows currents flowing in the internal ground conductor. Note that in Figure 6b the 60 Hz internal fundamental-current is lower than the harmonic currents. This is primarily due to the additive effect of harmonic currents in ground conductors. Figure 6a also shows additional spectral components not directly related to the power-line frequency. These additional frequency components are injected into the ground system by various nearby power consuming devices that induce currents back into the building power and ground conductors. All of these observed low-frequency components, may seem insignificant, but they can have devastating effects on susceptible systems [4].



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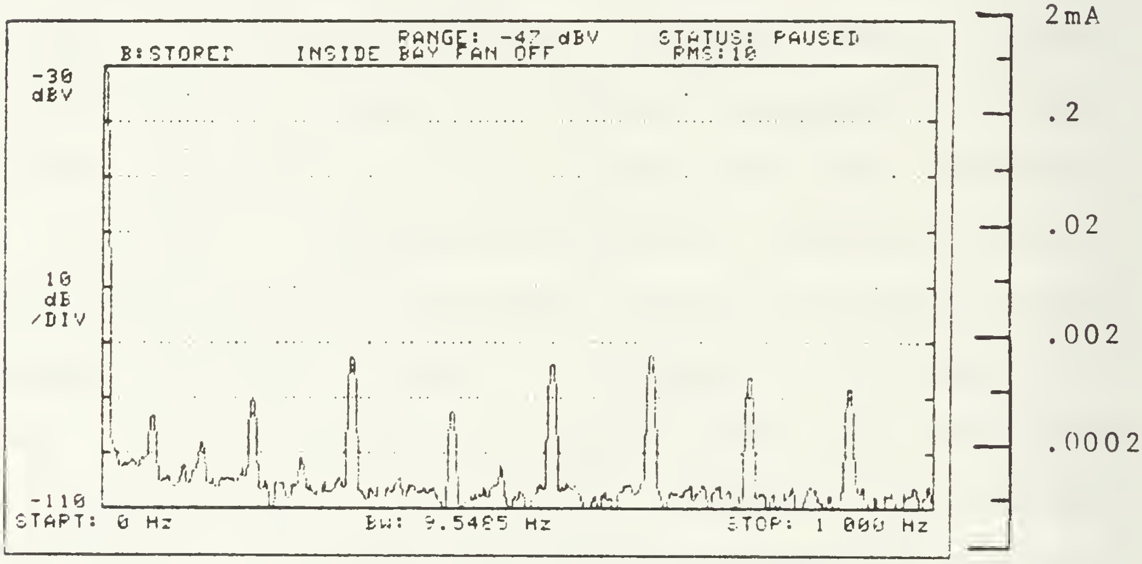
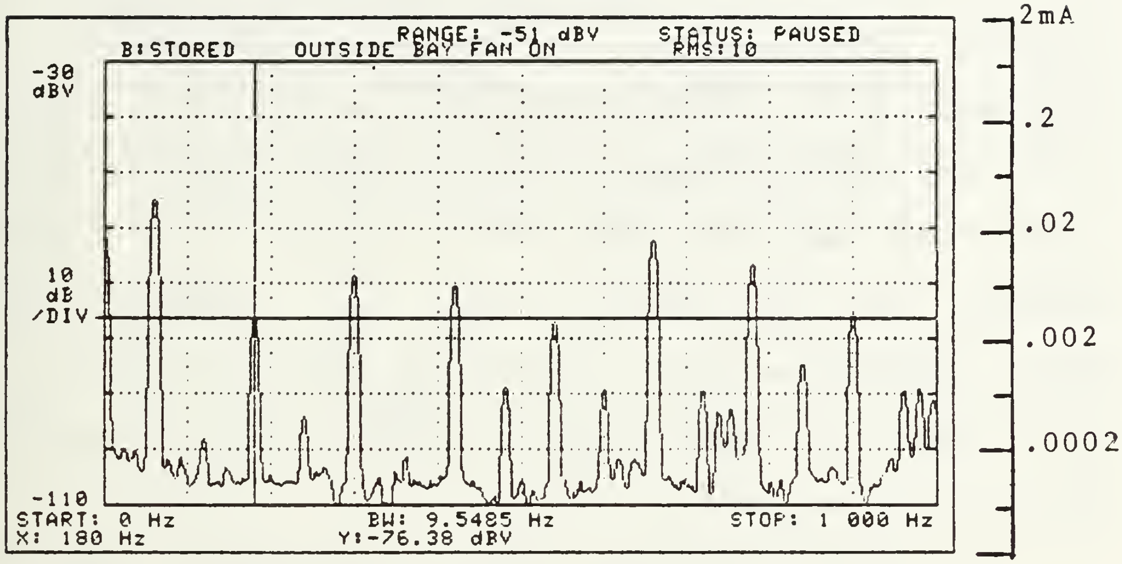


b)

Figure 6. Experimental Cabinet Outside and Inside Green Wire Current Internal Fan Off



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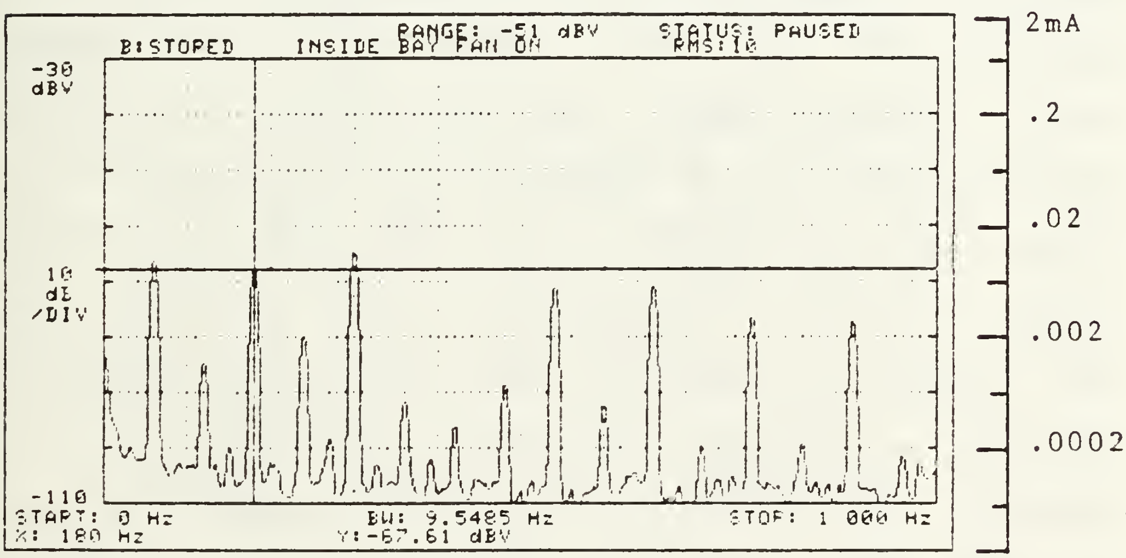


b)

Figure 7. Experimental Cabinet Outside and Inside Green Wire Current Internal Fan On

Figure 6b shows the significant reduction in fundamental and harmonic current levels between the outside and inside green-wire conductors, and the elimination of the external uncorrelated low-frequency components. The difference in the 60 Hz fundamental current level is nearly 40 dB, and the difference between harmonic currents is about 20 dB. The data show the external sources of fundamental, harmonic, and uncorrelated signals are returned to their source by the external conducting path provided by the barrier plate. Thus, these currents were prevented from entering the cabinet.

In Figure 7b the load level was noticeably increased by activating the ventilation fan located in the bottom of the cabinet. This fan injects significant ground return currents into the inside cabinet green-wire, creating a "noisy" internal ground. By turning on the fan we created a noise source that is isolated from the external cabinet green wire by the barrier plate. Comparing the top views in Figures 6a and 7a, there is now little difference between the internal and external green-wire currents because both external and internal sources of green-wire current are present. The increase of harmonic currents from the fan motor have increased internal cabinet harmonic levels which can couple into receiver circuits. The undesired fan motor

generated harmonics can be removed from the interior cabinet grounds by adding a similar barrier at the fan motor case.

B. BARRIER PLATE WITH RF LINE FILTER

The substantial reduction in harmonic coupling between the exterior and interior green wire has been achieved by providing internal and external current return paths by the barrier plate. EMI on the green wire is isolated effectively to either the "inside" or "outside" of the cabinet. This experimental practice has so far provided the necessary barrier for noise on the green wire, while at the same time maintaining the safety aspects of the green-wire required for personnel. Unfortunately, this direct path technique cannot be used directly to reduce the interference on the black and white (neutral) wires that also penetrate the cabinet.

Figure 8 shows the ambient level of RF noise current on the three wires that comprise the cabinet AC input in the Special Signal Processing Laboratory at the Naval Postgraduate School (NPS). The large level of noise current from 0-2 MHz tapers off somewhat out to 5 MHz. This noise level is typical of that found in laboratory buildings containing a variety of noise sources. This noise is coupled directly to the inside of the cabinet by the power conductors.

The AC line "noise" problem can be resolved by placing a filter at the barrier. The ideal solution would be to have a line filter which would be an open circuit to the AC line and a short circuit to the higher-frequency interference currents. This would allow these noise currents to be treated in the same manner as the green wire currents.

The filter designed for this part of the experiment is shown in Figure 9. The Pi-type filter is connected to both the internal and external surfaces of the barrier plate to provide decoupling of noise from both internal and external sources. As configured, the .01 microfarad capacitors (1500V rating) conduct the high-frequency components in both the black and white wires to the barrier surfaces while the ferrite core inductors provide the attenuation to the RF signal. This attenuation appears as a noise voltage across the inductor which is bypassed to the appropriate surface of the barrier plate. The filter cut-off frequency is high enough to pass the 60-Hz power current, but also low enough to attenuate most of the high frequency noise.

Figure 10 shows the Micro-cap II program generated frequency response of the filter. Note the undesired sharp resonance peak in the test filter at approximately 150 KHz. This resonance would be eliminated in a final design. Above this frequency, signals are attenuated at about 12

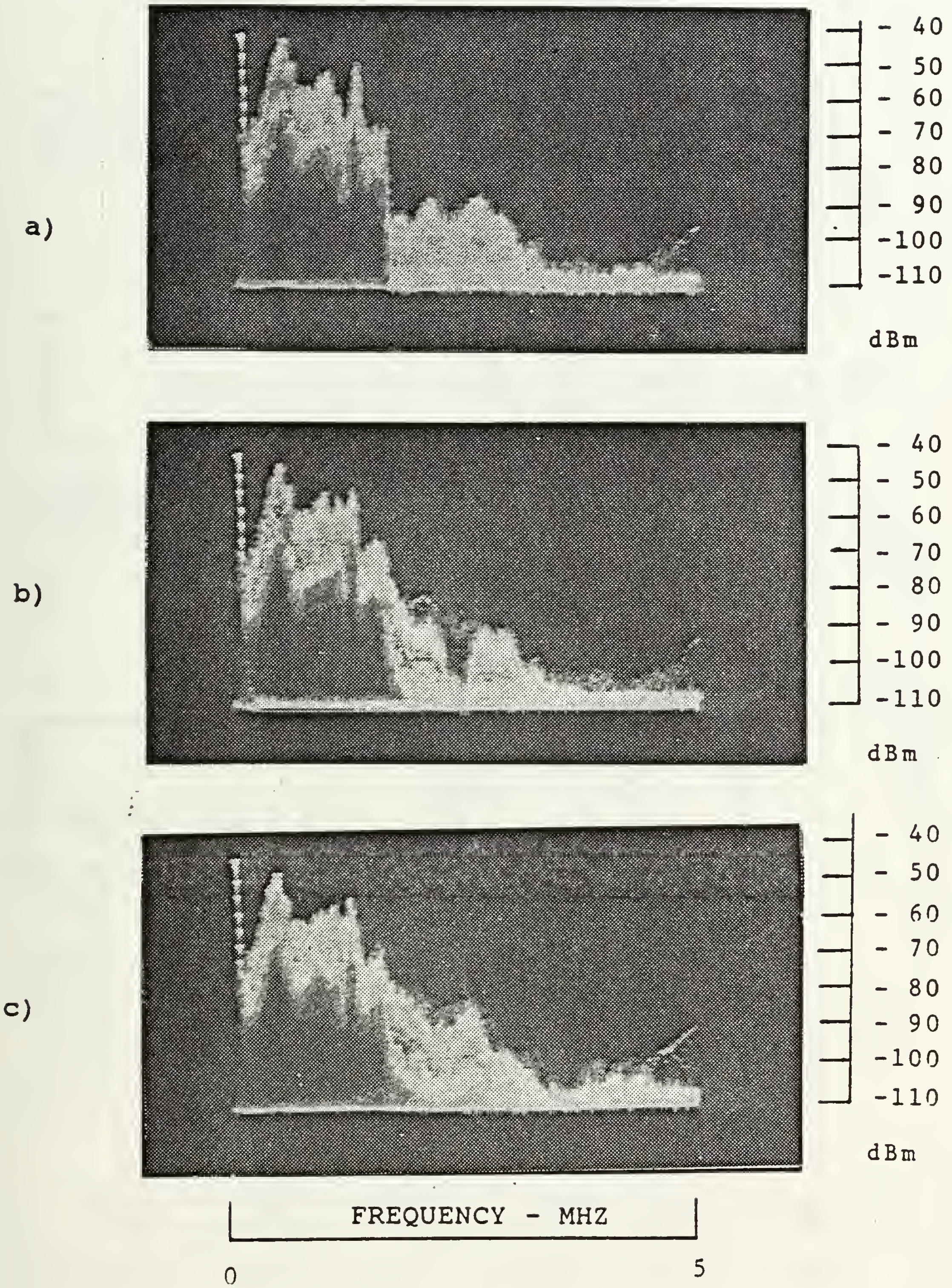


Figure 8. Green, White, and Black AC Line input to Experiment Cabinet

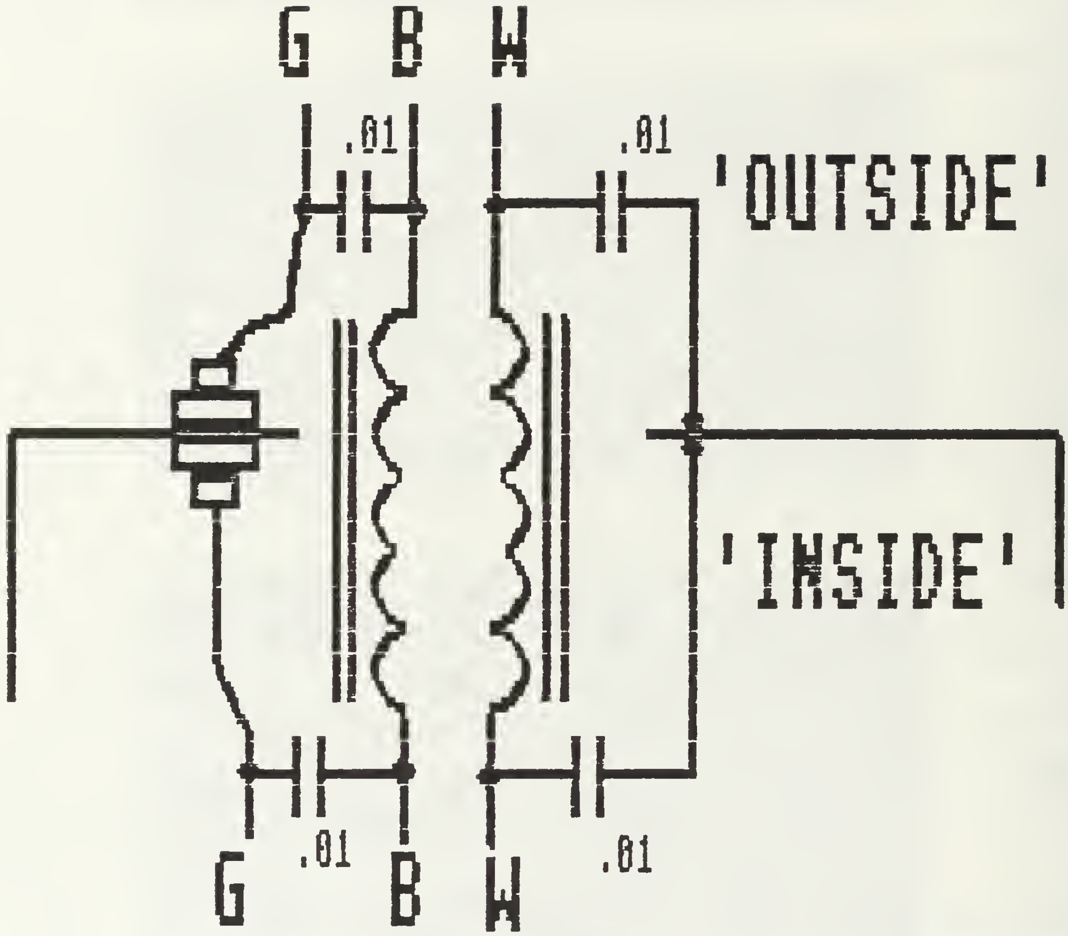


Figure 9. Experimental Power Line Filter Configuration

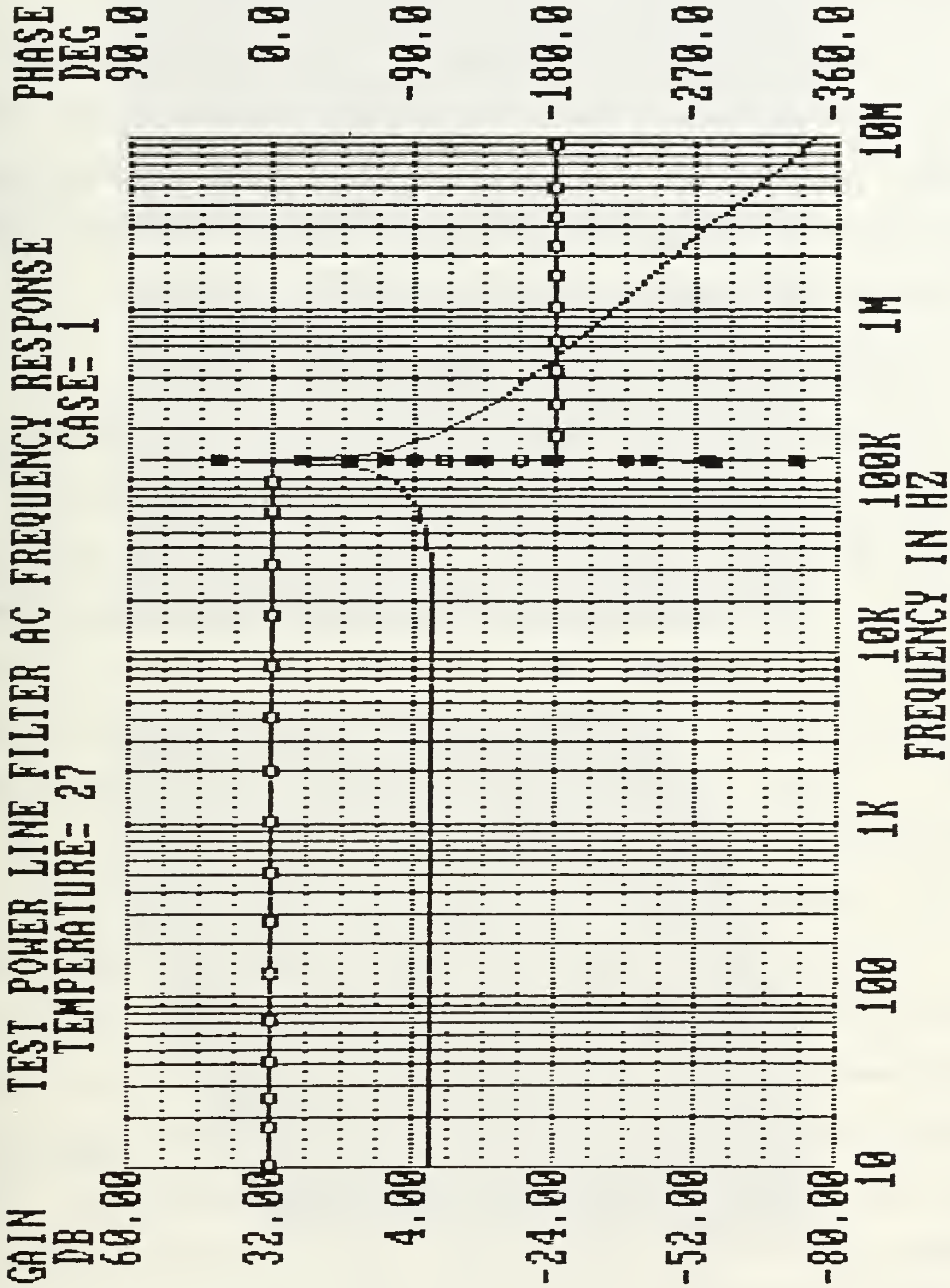


Figure 10. Test Power Line Filter AC Frequency Response

dB/octave. The results of inserting the filter into the AC line are seen in Figures 11,12 and 13.

Although this design shows a significant reduction in noise coupling, it is by no means an optimum power line filter. The test filter was used to demonstrate that noise on the power input lines can be significantly reduced with a filter on the barrier plate.

C. PENETRATING CONDUCTOR EXPERIMENTS

It has been stated previously [1] that changes in either geometry or physical size of an opening or penetration may effect a change in the propagation path of a conducted interference. It has also been proven that changes in frequency are reflected as changes in the impedance median and therefore the noise conductive path [8]. These changes, as well as some others, are investigated during this portion of experimentation.

1. Penetrating Wire Measurements

Figure 14a shows the experimental test set-up used during the majority of the penetrating conductor experiments. As configured, the spectrum analyzer will display signals from 0-20 MHz. A preamplifier with 11 dB gain was used to improve measurement dynamic range. The output of the noise generator was set to provide +20 dBm of broadband noise when terminated with a 75 ohm load. This figure also shows the measurement configuration for test

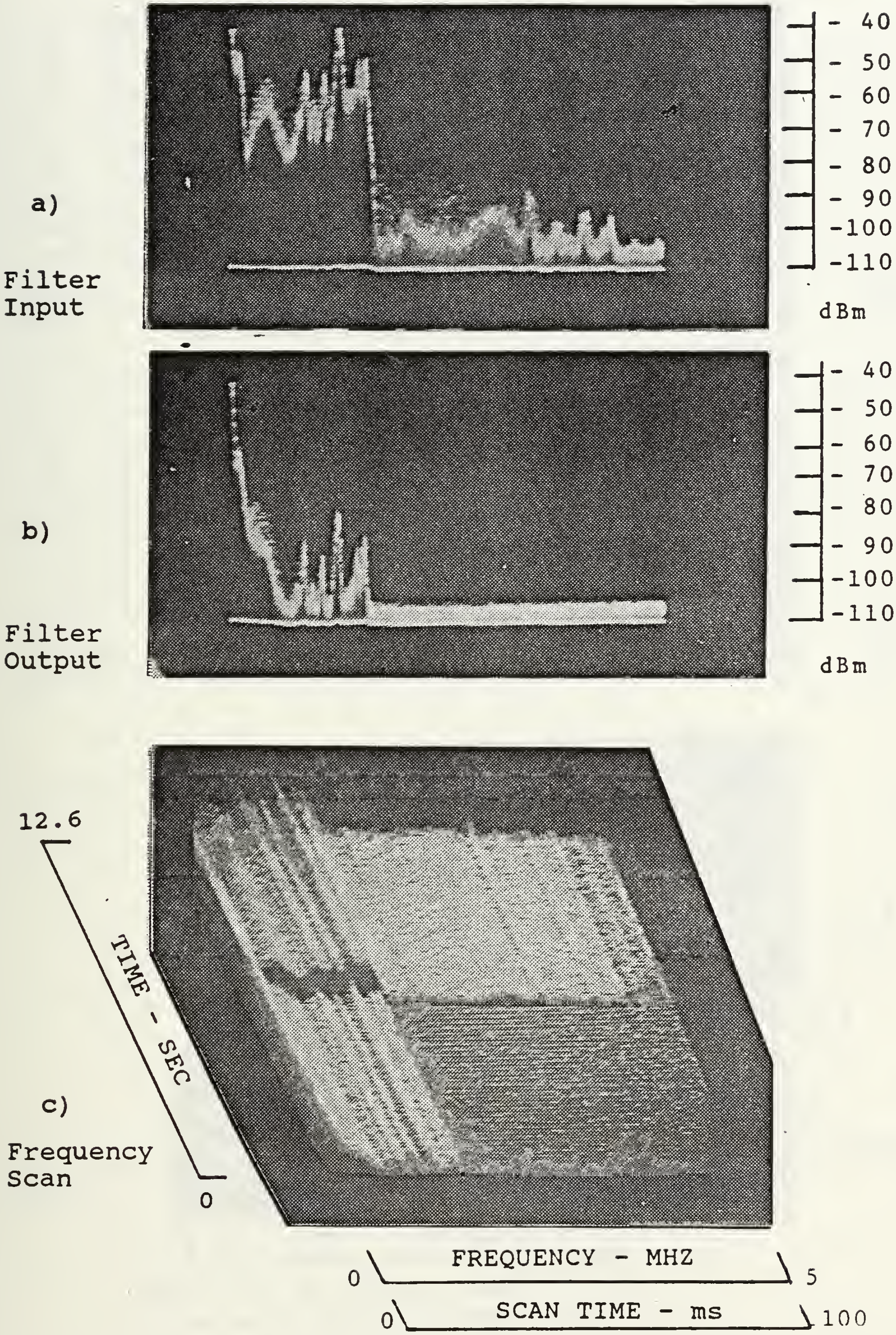


Figure 11. Green Wire Filter Input and Output

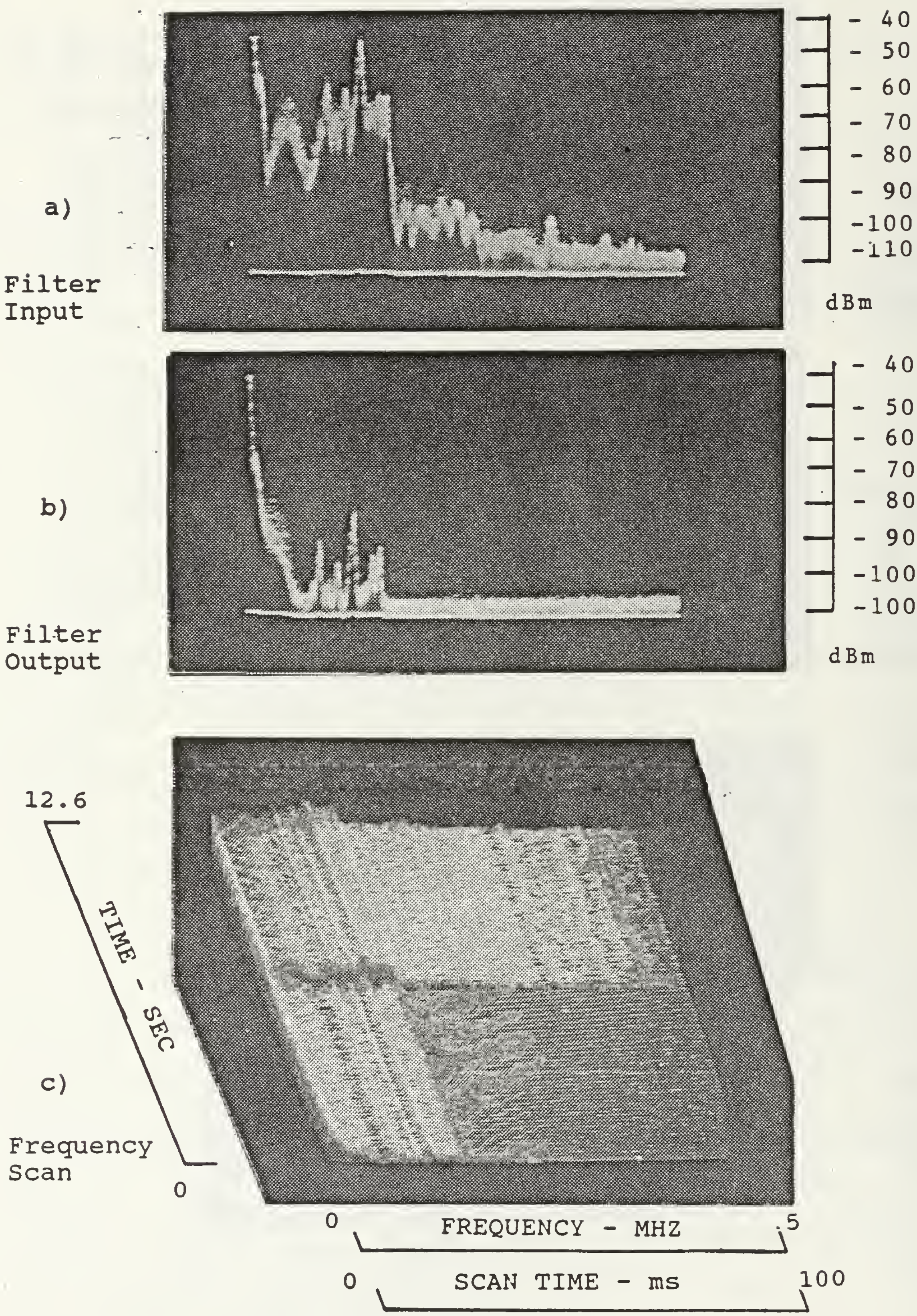


Figure 12. White Wire Filter Input and Output

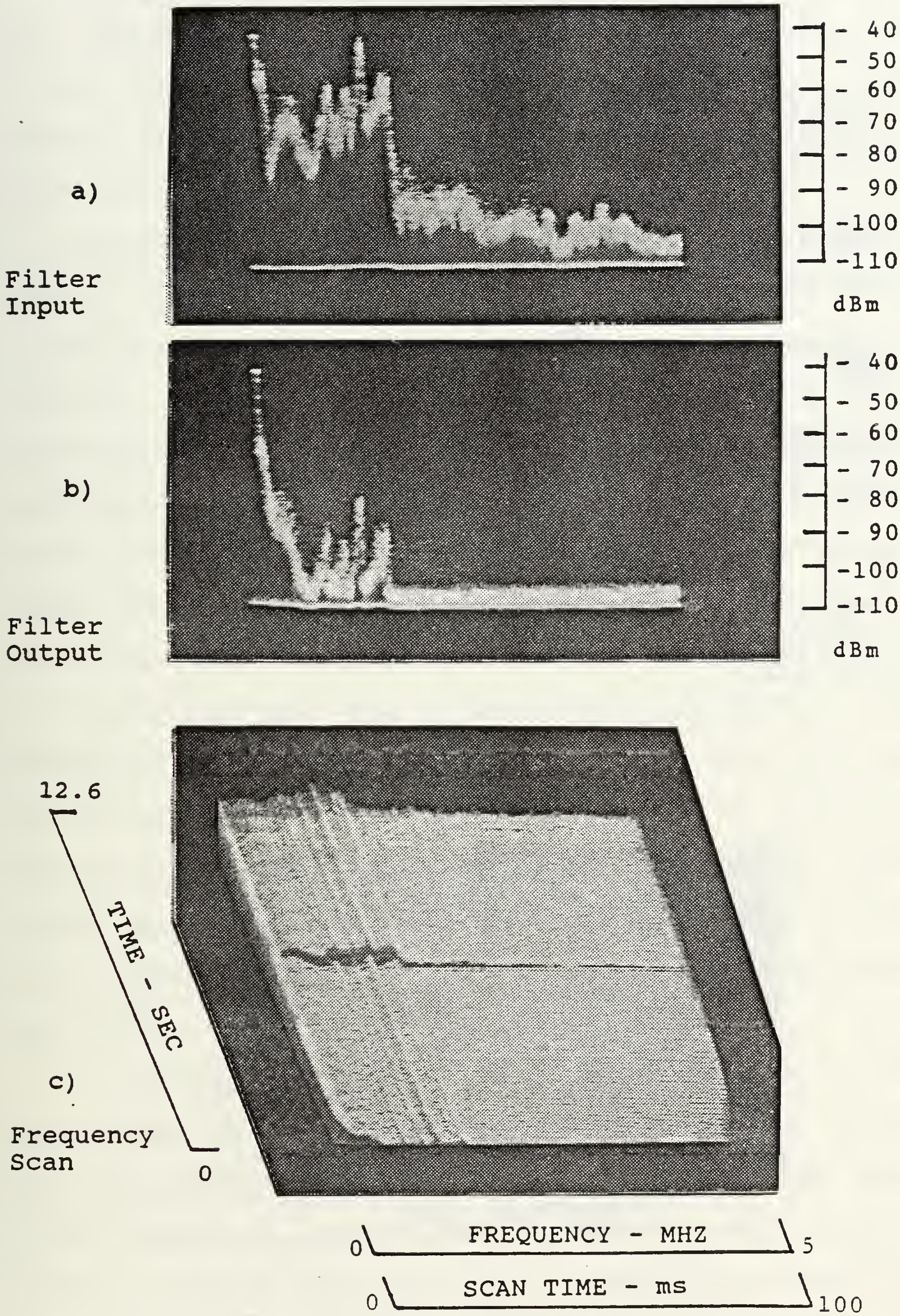


Figure 13. Black Wire Filter Input and Output

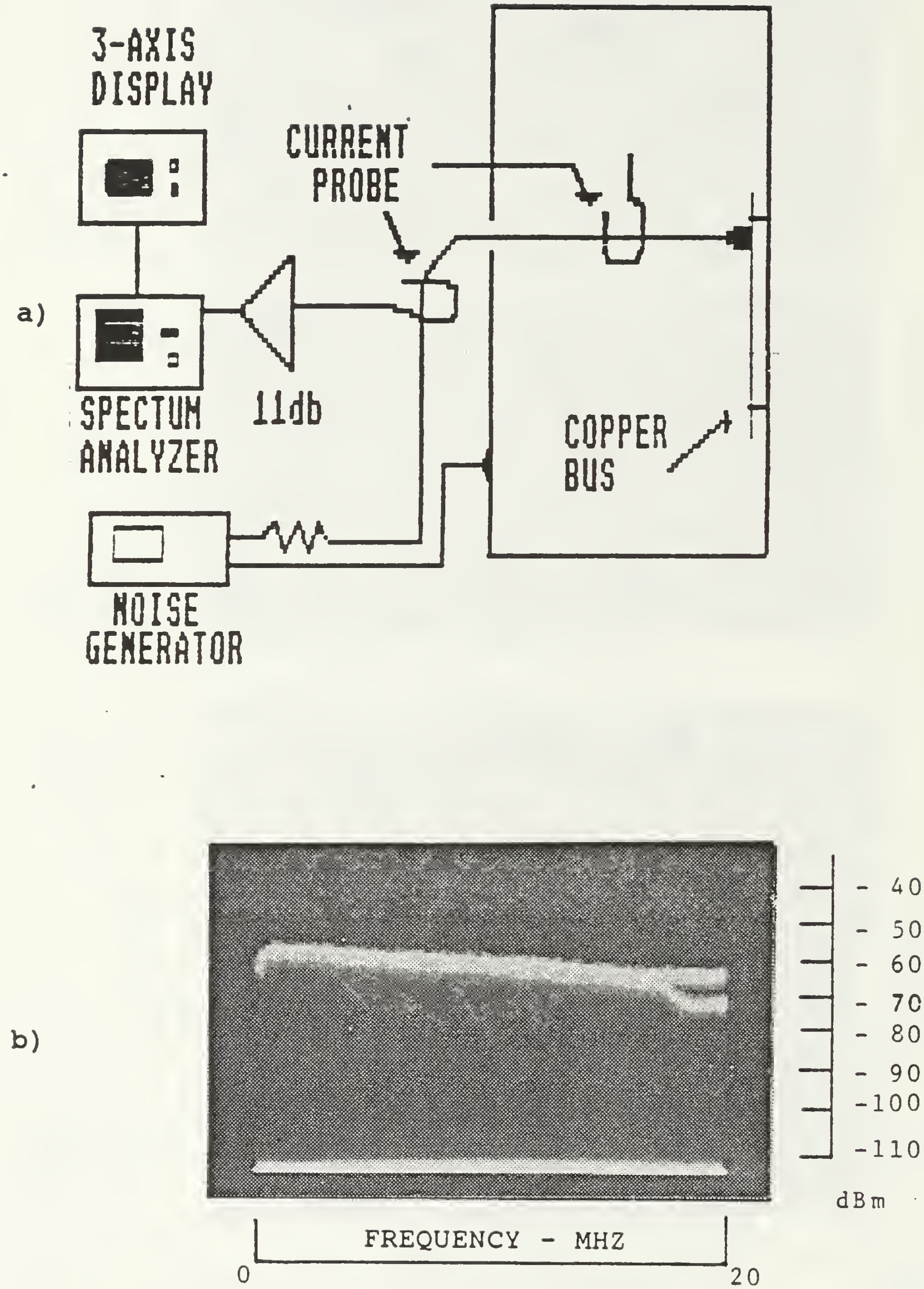


Figure 14. Penetrating Conductor Test One

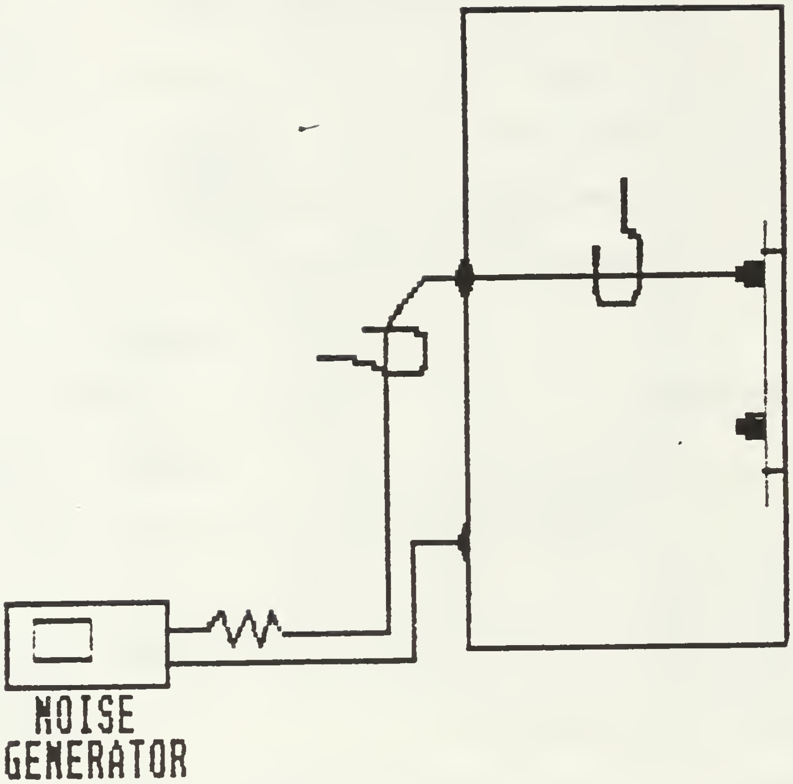
one. The noise generator was connected through a small hole in the side of the cabinet to the inside cabinet copper ground bus. The common side of the generator is firmly connected to the outside skin of the cabinet.

Figure 14b shows both the inside and outside noise current on the penetrating conductor as measured with a current probe. This test shows noise conducted through an untreated penetration of the cabinet. There is little difference in current amplitude between these two measurements. A slight dip was noted on the inside cabinet current measurement at about 18 MHz. This is probably because of the capacitive coupling between the conductor and the cabinet wall at the hole.

In Figure 15a the configuration for test two was changed to simulate a proper topological barrier. The noise conducting wire is bolted to the outside of the cabinet, and the inside wire (which is connected to the internal cabinet copper bus) is connected to this same bolt. The bolt was firmly secured with a nut and a similar set of measurements were taken.

In Figure 15b significant differences can be seen between current on the inside and outside wires. This is strongly apparent at very low frequencies, and from 10 MHz-20 MHz, where the shorter outside conduction path and skin effects play an important role. Resonance effects and

a)



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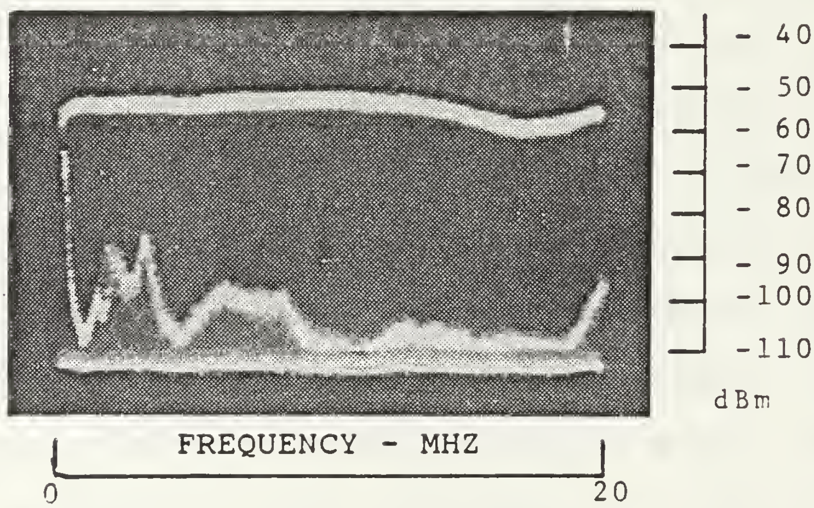


Figure 15. Penetrating Conductor Test Two

cabinet radiation leakage are probably the reason for the higher levels of inside current observed between 0 - 10 MHz and near 20 MHz. The minimum isolation of 30 dB is direct evidence of the effectiveness of the proper topological barrier approach.

In Figure 16a, test three, the test configuration has been changed by placing the noise generator inside the cabinet. Here the noise generator is connected by a wire between the top of the internal ground bus and the inside wall of the cabinet. The bottom of the ground bus is connected to the same side wall, but to a separate bolt. The purpose of this experiment is to determine the current distribution on conductors inside the cabinet. As shown in the bottom of this figure, about the half the current is conducted through the wire connected between the bottom of the bus bar and the inside wall. This was expected because of the small differences in the impedance of the bus bar to inside wall and the cabinet inside wall paths. With this inside cabinet current division it would seem that the internal noise source could be coupled outside of the cabinet via a conductor connected to the inside wall.

Figure 17a, test four, shows the cabinet with the wire now connected from the inside bus bar to the outside cabinet wall via a small hole on the side. Figure 17b shows the difference in current between the inside, and the inside to

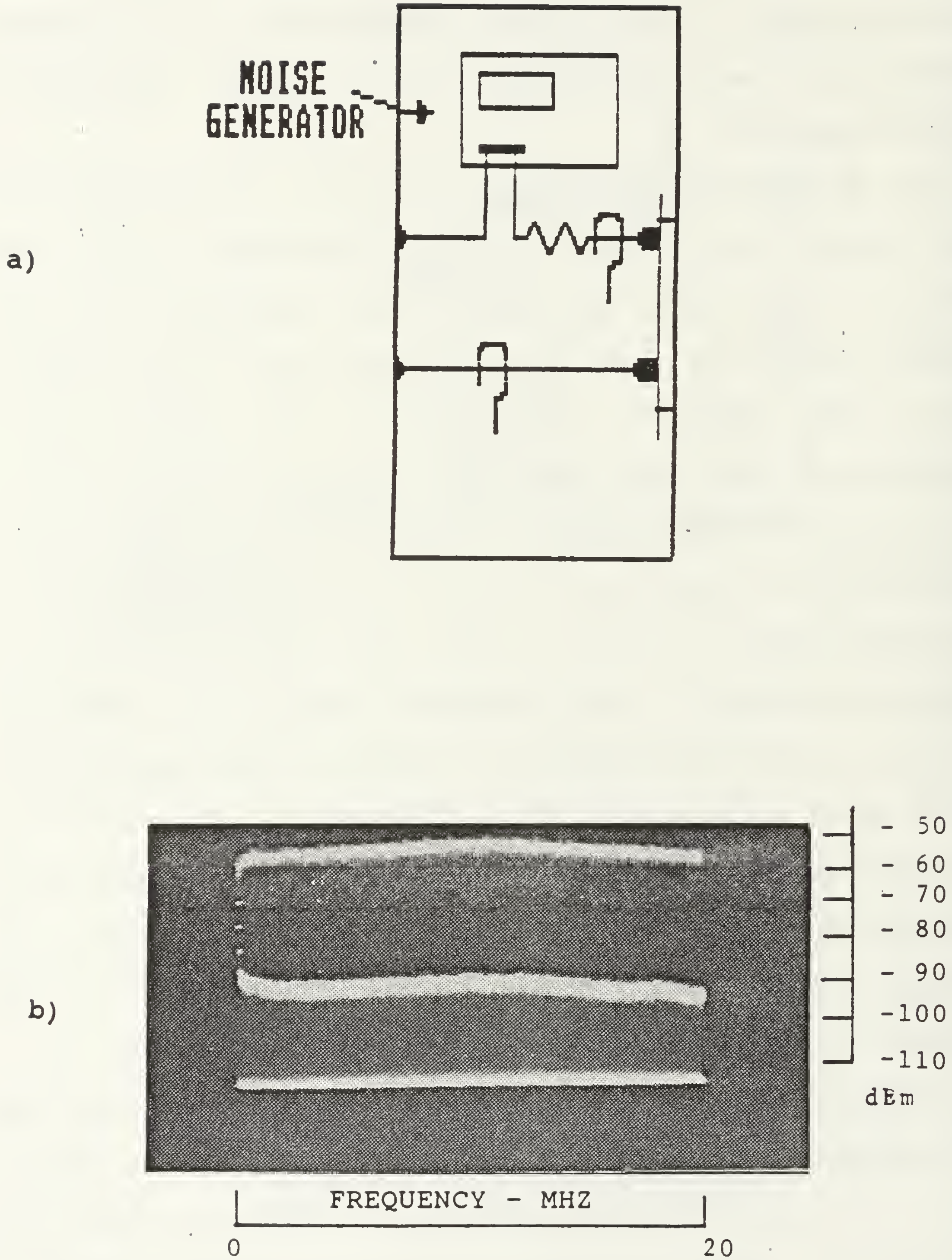


Figure 16. Penetrating Conductor Test Three

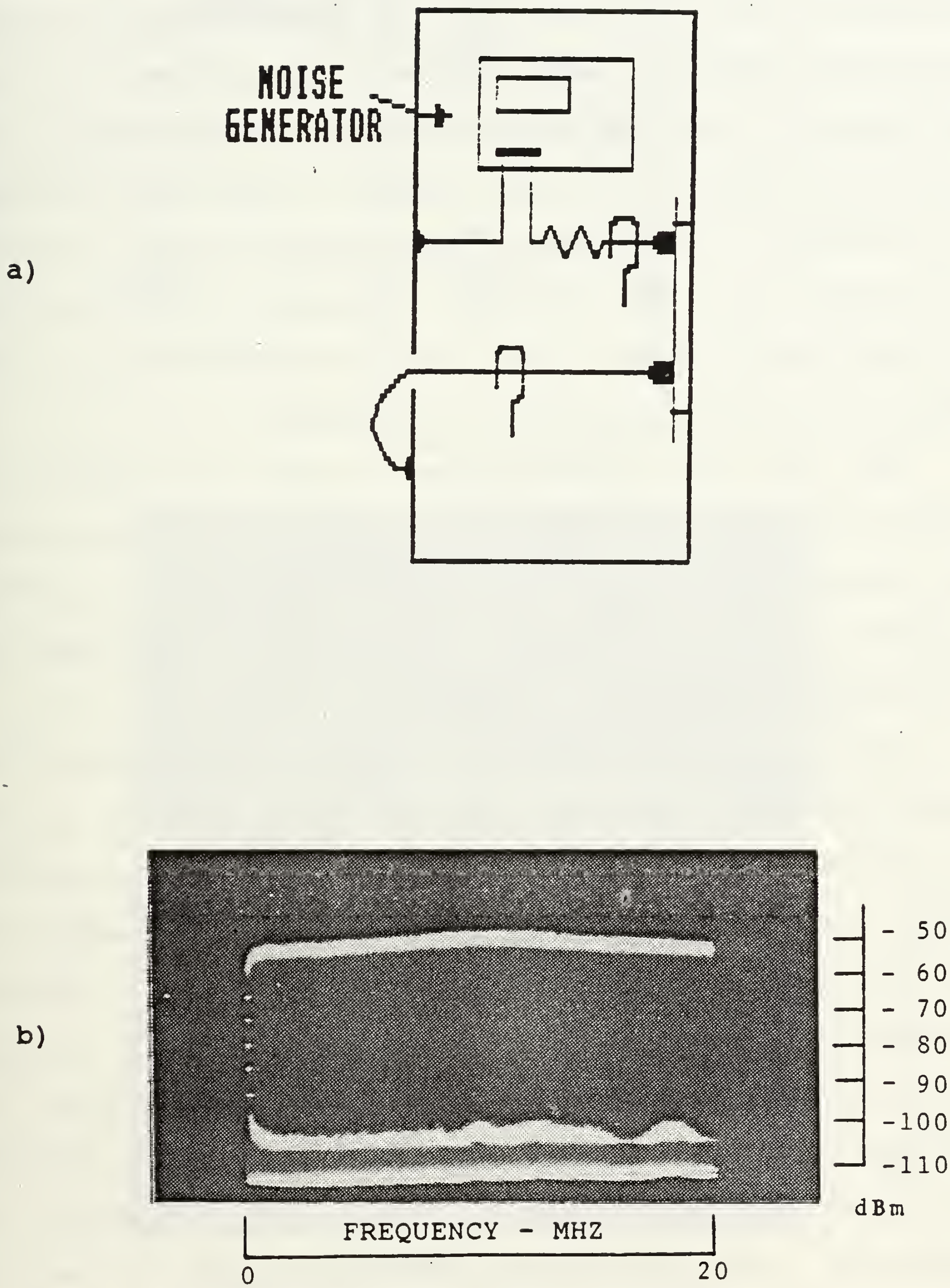


Figure 17. Penetrating Conductor Test Four

outside paths. Notice how little current is conducted to the outside surface. This is due to the very low impedance provided by the inside path for the noise currents compared to the high impedance path provided by the inside to outside surface path. The wall conduction path is represented as an absorption loss to the noise current. This high frequency loss provided by the cabinet metal skin is about 9 dB per skin depth [8]. The broadband isolation provided by this configuration is about 50 dB, and is representative of the amount of isolation provided by the cabinet.

The test five configuration is shown in Figure 18a. Noise current was injected into the internal cabinet ground bus. The bus has connected an external ground via a cabinet penetration. This configuration is similar to that employed for cabinet grounds in Bullseye sites.

The measurements in Figure 18b and 18c for test five show noise current on the inside and outside ground conductors. The spectral shape of the flat, broadband noise source was modified by the frequency-dependent impedance of the long ground lead and building ground system. Cabinet generated noise current is now injected into the building ground system, and this current is conducted throughout the building on the ground system. The current is then returned to the cabinet source by the power wires, including the green-wire. This complex and uncontrolled path for the flow

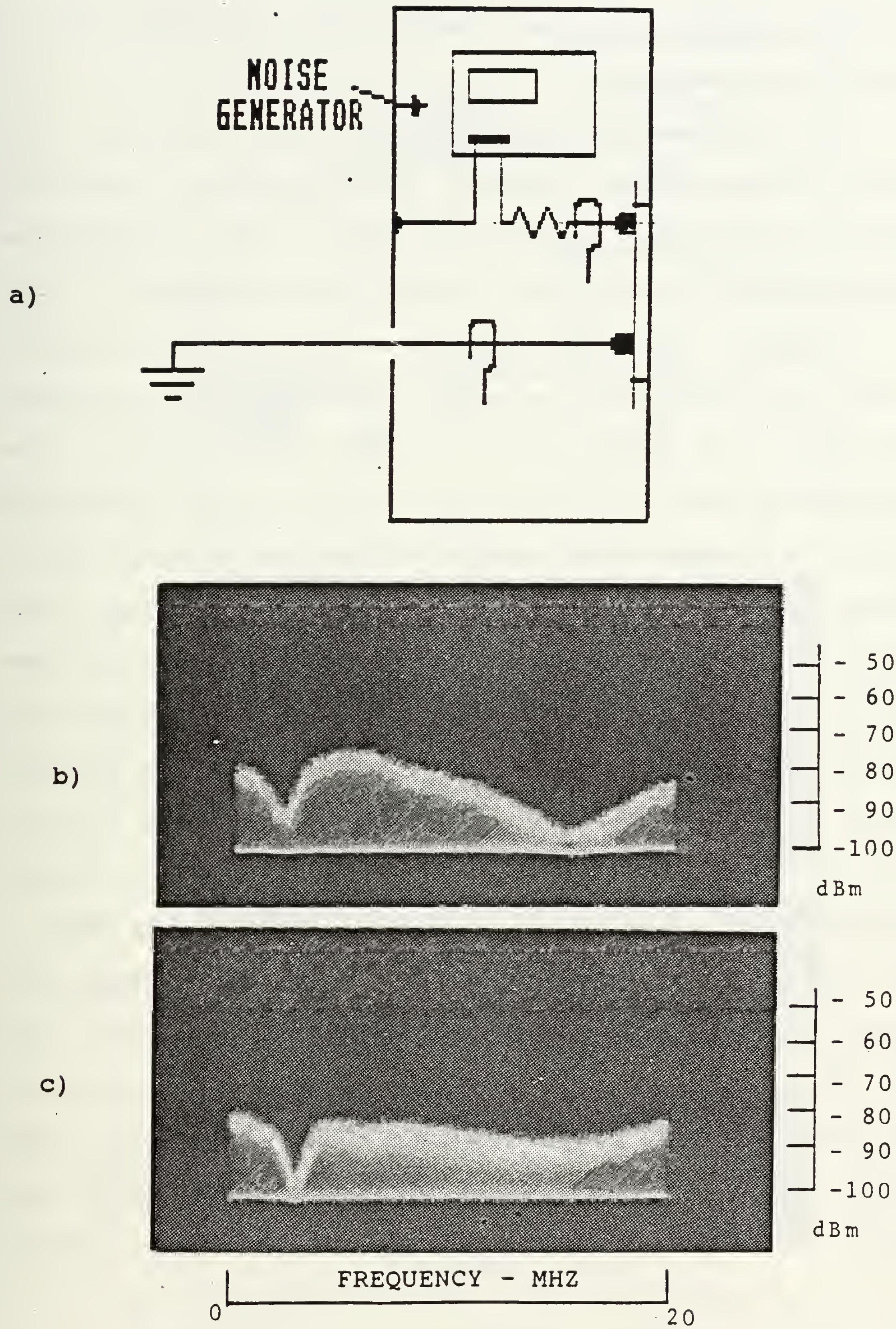


Figure 18. Penetrating Conductor Test Five

of ground current provides numerous paths for the flow of RFI and noise currents.

The configuration of test five also permits noise current from external sources to be conducted into the cabinet by the penetrating ground wire. Thus, uncontrolled grounding cannot be used for control of interference.

In Figure 19a, test six, the configuration is similar to that used for test five except that the ground conductor penetration was changed to a barrier configuration. The measurements taken here show (1) noise currents inside the cabinet, (2) between the outside cabinet and ground, and (3) between the outside cabinet and ground with the noise generator turned off. The significance of this experiment is the use of barrier grounding to effectively isolate the "inside" of the cabinet from the "outside" of the cabinet. As can be seen in Figure 19c there is very little coupling of noise outside of the cabinet. The inside to outside decoupling was more than 40 dB except near 20 MHz where a small amount of radiation noise was noted. Because the minimum noise in Figure 19c was difficult to interpret, the noise generator was turned off. The noise off data are shown in Figure 19d. In this figure the small noise peaks near 20 MHz disappeared and the measurement confirms that ambient noise was observed at lower frequencies. Ambient

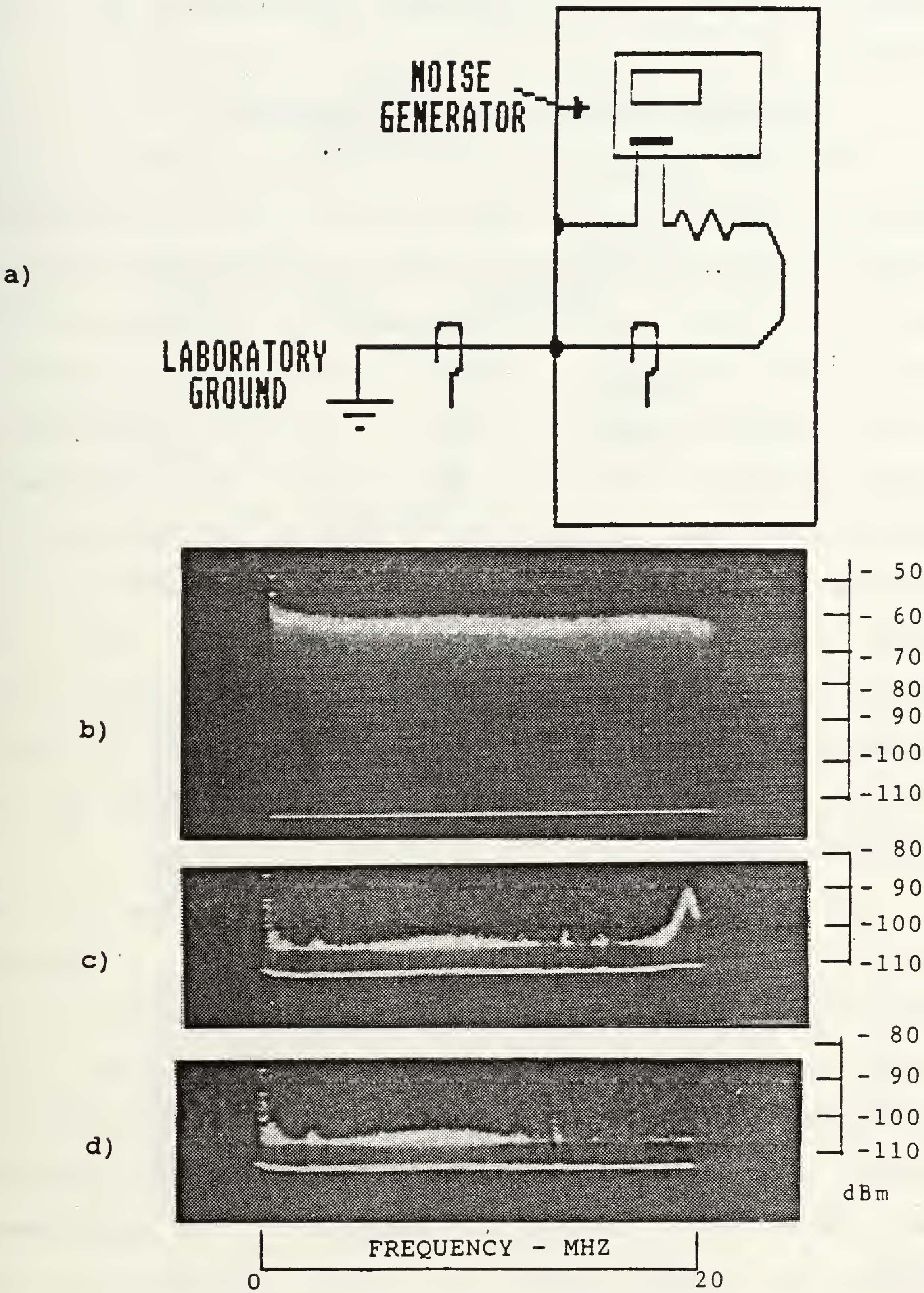


Figure 19. Penetrating Conductor Test Six

noise prevented making isolation measurements at lower levels.

2. Penetrating Coaxial Cable Measurements

The next experiment, test seven, examined shield current on a penetrating coaxial cable. In this experiment noise is injected into the internal coaxial shield and the other end of the cable is fed through the front panel of the cabinet and connected to an oscilloscope. This represents a typical penetration of a cabinet for a test measurement. Figure 20a shows this test configuration. This experiment demonstrates that, although the closed conducting shield of the coaxial shield is used to control interference, it can also provide an unattenuated conduction path for interference currents. Figures 20b and 20c show noise currents from the inside of the cabinet are passed, with a very slight change, through a cabinet penetration to the oscilloscope.

In Figure 21a, the test set-up is changed so the coaxial cable is no longer fed through a cabinet penetration. A BNC bulkhead connector was installed on a panel, and used in place of the cabinet penetration. The measurements now show a significant difference between coaxial cable shield current inside the cabinet and outside the cabinet (see Figures 21b and 21c). The difference between the current levels is a direct indication of the

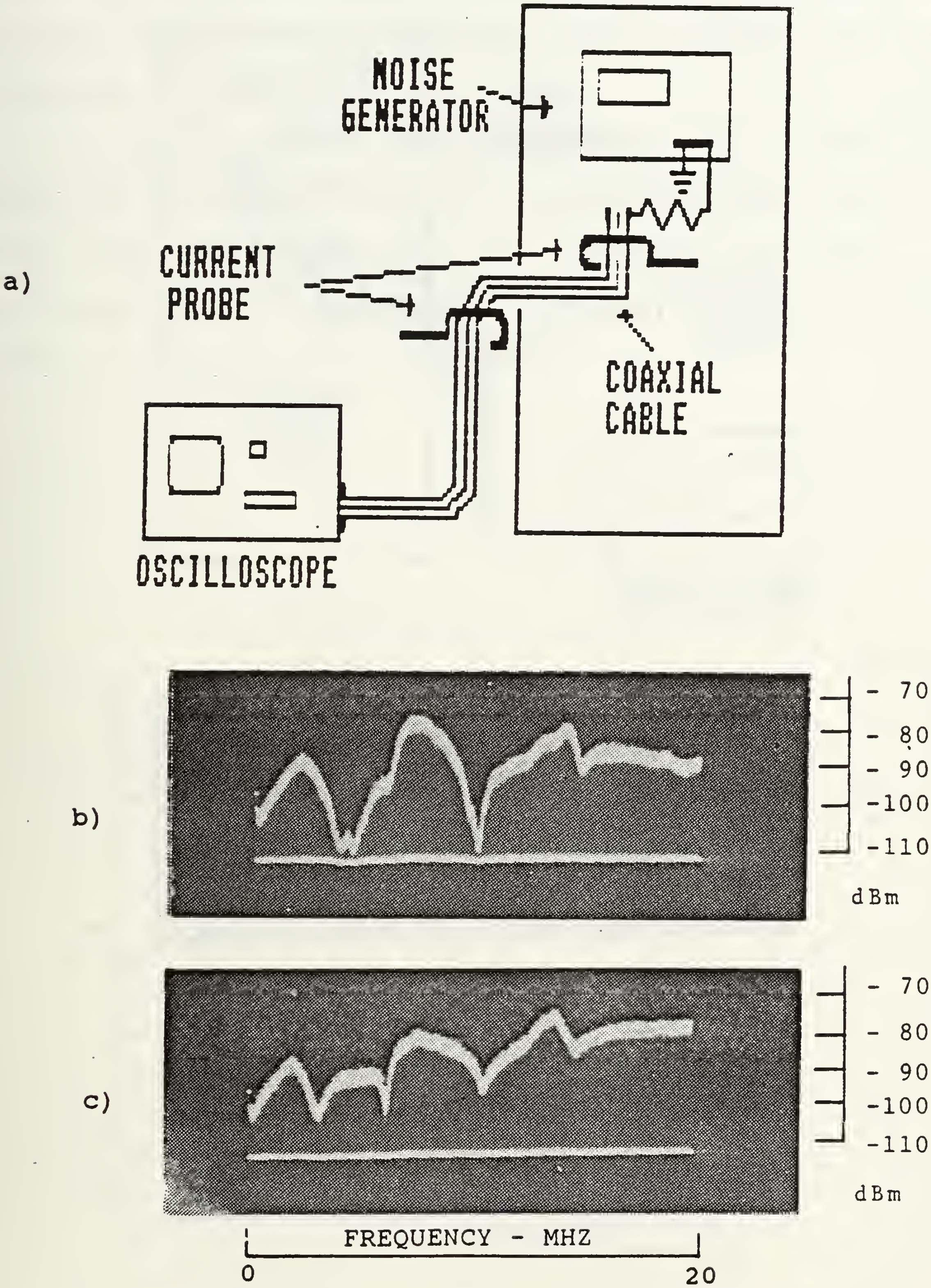


Figure 20. Penetrating Conductor Test Seven

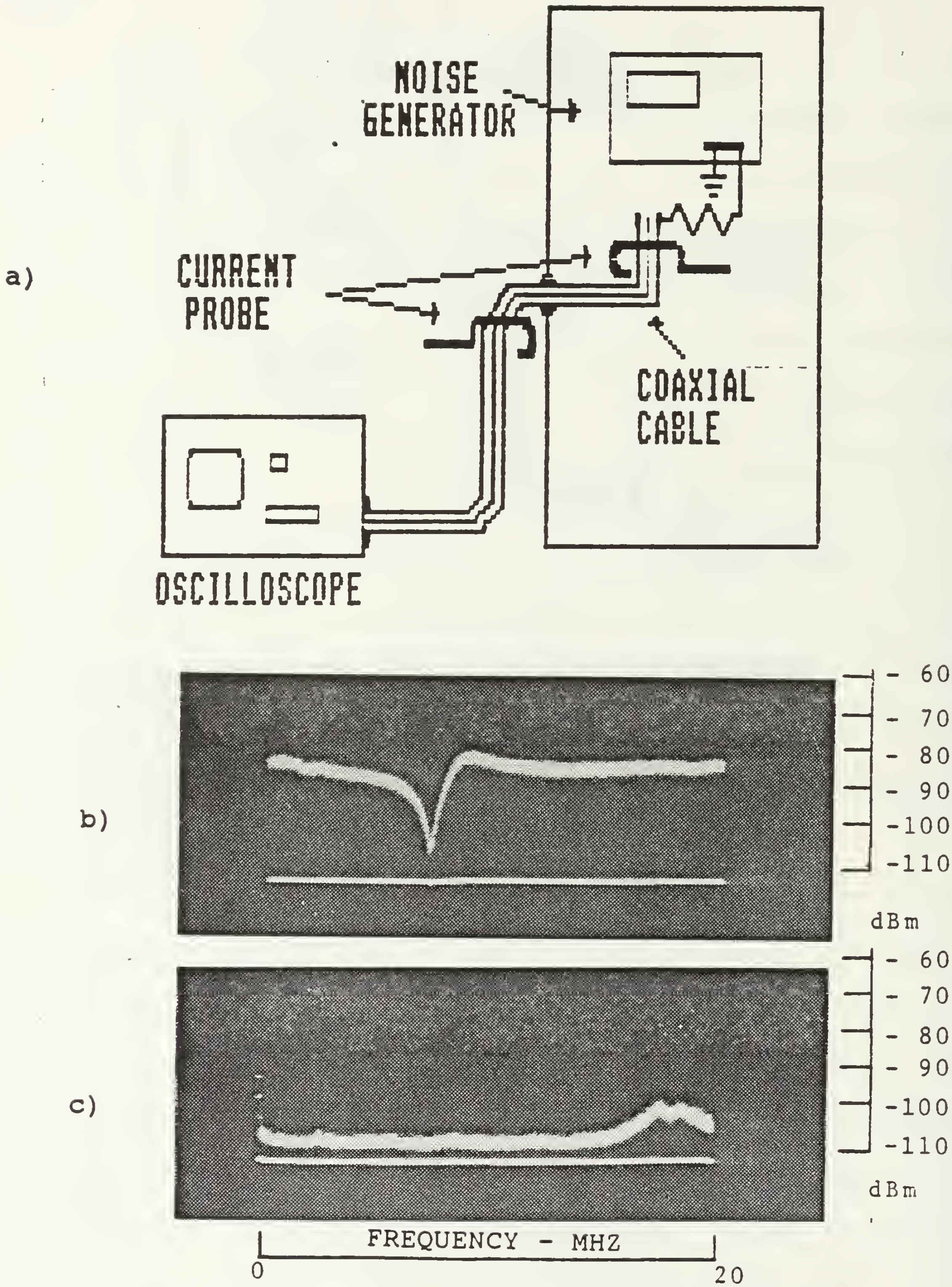


Figure 21. Penetrating Conductor Test Eight

amount of isolation provided by the panel and BNC feed through. Except for a resonance notch at about 7 MHz the isolation is about 25 dB.

The previous experiments demonstrated that broadband EMI rejection can be provided by a standard equipment cabinet. They also show that proper grounding and treatment of penetrating conductors is necessary to make this cabinet an effective barrier to interference.

IV. FIELD SITE STUDIES

A. INTRODUCTION

The Signal to Noise Enhancement Program (SNEP) of the Naval Space and Warfare Systems Command (SPAWARS) has been tasked to improve the signal-to-noise levels in the RF-Distribution Systems of Navy HFDF sites. The program usually includes (1) a survey to identify the extent of degradation of site performance from both internal and external man-made noise sources, and the identification of mitigation actions needed to improve site performance, (2) a site upgrade program, and (3) post upgrade measurements to further evaluate site performance. Site performance is defined as the ability of a site to receive and define characteristics of target signals in the presence of ambient noise levels in the RF-Distribution System.

Part of the SNEP noise reduction effort is the installation of barrier plates in cabinets housing components of the RF-Distribution (RFD) system. This installation provided an opportunity to investigate the performance of barriers in an operating site. Field measurements of green-wire current and ground current were made, prior to cabinet modifications, at both Northwest and Sabana Seca. In addition, internal and external green-wire

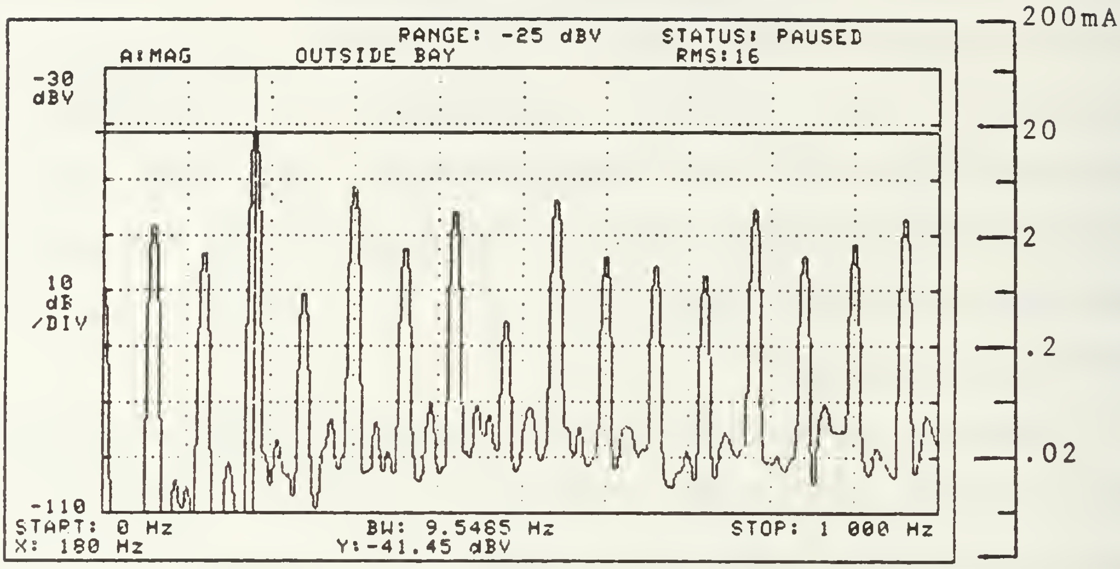
currents were measured at both sites after cabinet modifications were completed. Examples of green-wire current values are provided in this chapter. These examples supplement the laboratory measurements of interference isolation described in Chapter Three, and they provide direct evidence that barrier techiques can be applied to practical field problems.

B. NSGA NORTHWEST

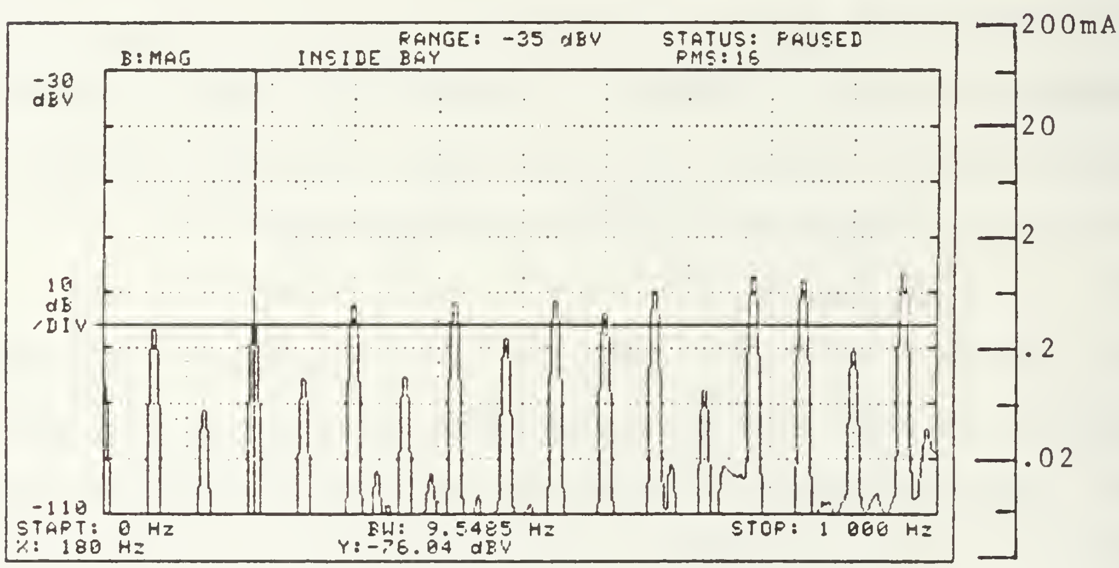
Barrier plates were added to cabinets housing equipment in the RFD system at NSGA Northwest, Virginia. These plates provided barrier isolation for power conductor green wires and for the cabinet ground conductors. External and internal green-wire currents were measured at all equipment cabinets in the RFD system. Selected cases of internal and external ground conductor current were also examined. Representative examples of green-wire isolation provided by the barrier plates are given in this section.

1. Site Results

Figure 22 shows external and internal green-wire current for Bay 34 at the fundamental frequency of the power line and for harmonics 2 through 16 after the installation of a cabinet barrier plate. The current scale on the right side of the views is accurate for frequencies above 180 Hz. At lower frequencies scaling factors (-2dB at 120HZ and -5dB at 60HZ) must be used to obtain actual current values.



a)



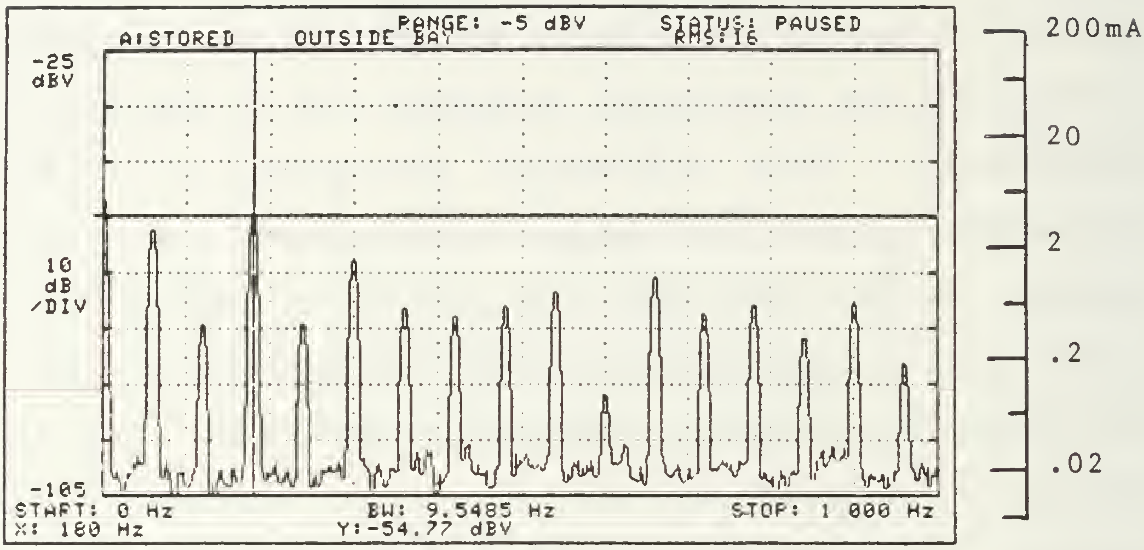
b)

Figure 22. Bay 34 Outside and Inside Green Wire Current

However, the outside and inside values of current can be compared without using the scaling factors. The external current in Bay 34 is 15 to 35 dB higher than the internal current at the fundamental frequency and at the low-order harmonics. This difference decreases as frequency increases. Since both external and internal bay harmonic sources exist, the data in Figure 22 represents the difference in fundamental and harmonic amplitude between the external and internal sources rather than the total isolation provided by the green-wire barrier. Since internal harmonic generation by the multicoupler power supplies in Bay 34 is low, and the external sources of harmonic current are considerable higher, the measurement provides an excellent indication that good isolation was achieved by the installation of the barrier plate.

A direct measurement of the isolation would have required the shut-down of all equipment in the cabinet. This was not done to avoid site outage. The simple measurement of differences in harmonic levels was sufficient to determine the proper operation of the barrier plate.

Figure 23 shows similar measurements for Bay 77. Again, the external green-wire current was considerably higher than the internal current. The data show that considerable isolation was achieved by the barrier plate,



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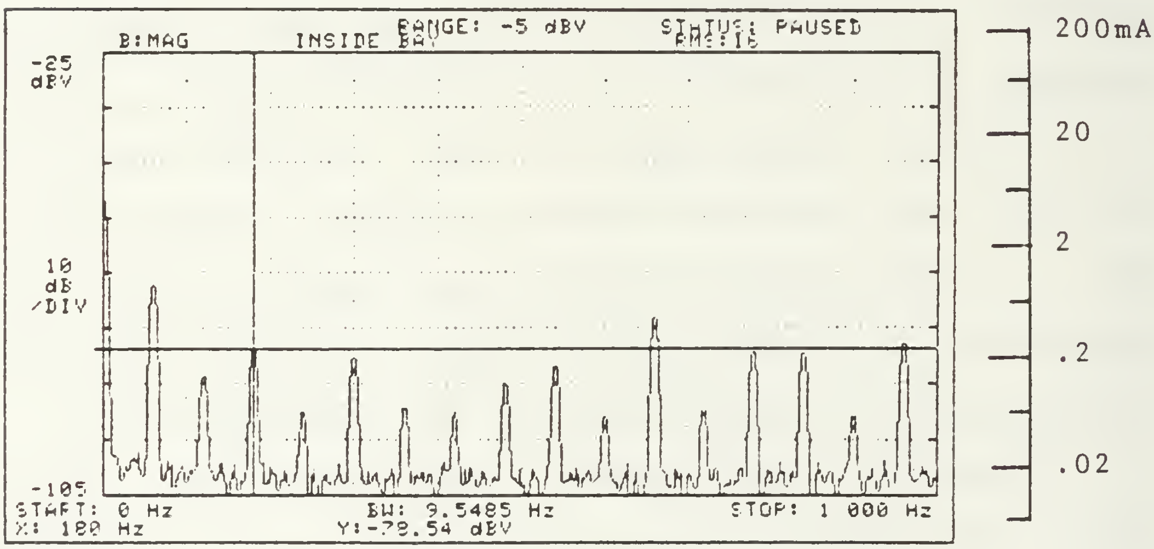


b)

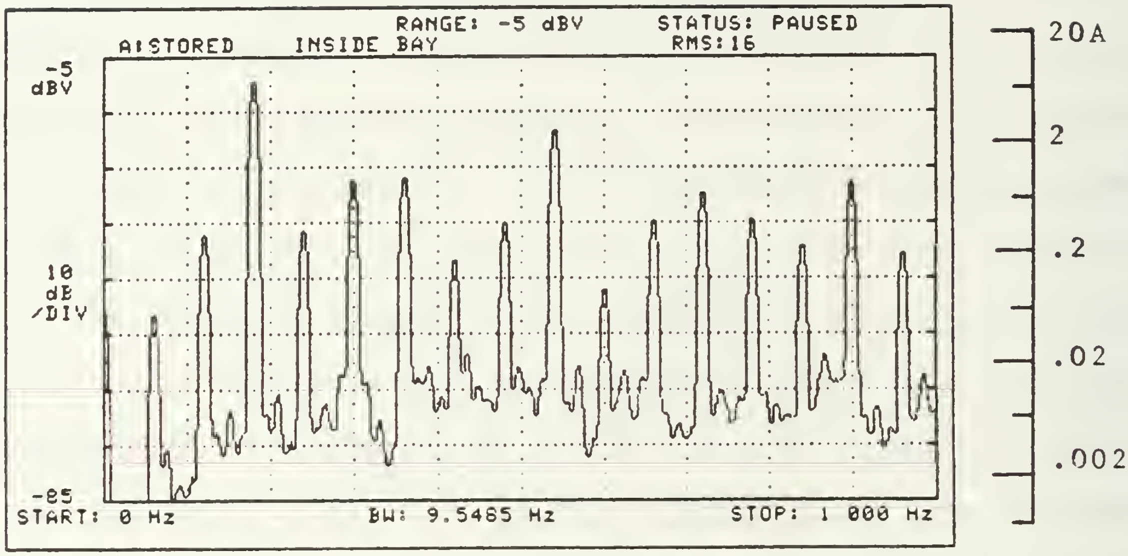
Figure 23. Bay 77 Outside and Inside Green Wire Current

but the maximum values of isolation were not defined by this simple measurement.

Abnormally high internal green-wire currents were found in Bay 76. Internal current actually exceeded the external current by a large amount. Figure 24 shows internal current levels (about 8 Amps at 180 Hz). Equipment in the bay was examined, and their power cords were unconnected. When the power cord from an unused power supply (turned off) was removed, the internal green-wire current decreased to low values as shown in View (b). Investigation of the power cord to the power supply showed that the white and green wires had been interchanged, resulting in a ground loop between the white conductor and the green safety conductor. The measurement of green-wire current identified the presence of the faulty wiring and permitted immediate corrective action to be taken.

The green-wire currents were reexamined after the fault was corrected. Figure 25 shows external and internal green-wire current for Bay 76 with the correct power cord connections. Normal green-wire current differences were obtained when the faulty power supply plug was repaired, indicating that good isolation was achieved.

Measurements on Bays 54 and 55 indicated that external and internal green-wire currents were about equal. This suggested that either no isolation was achieved, or the



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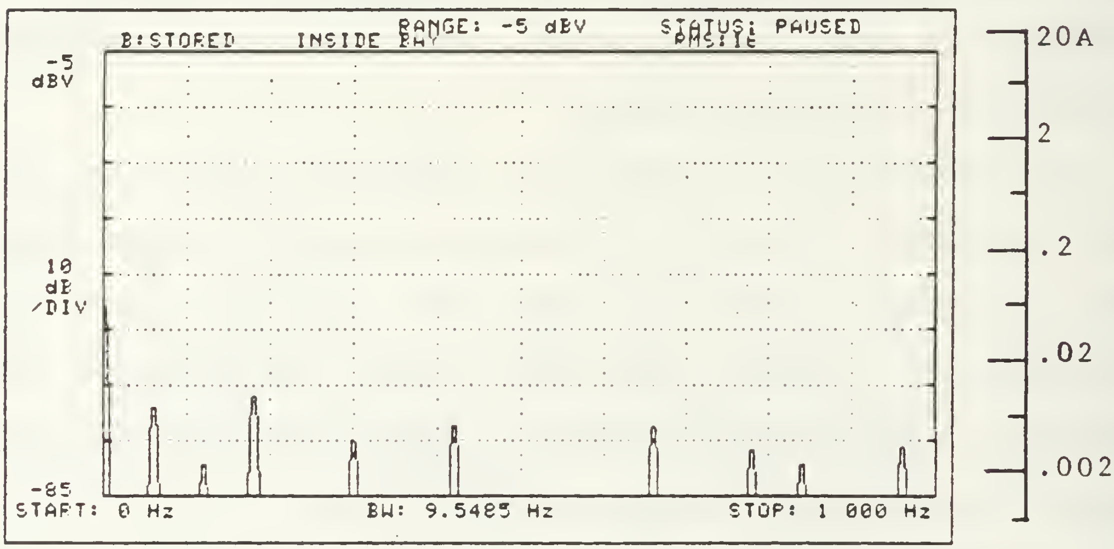
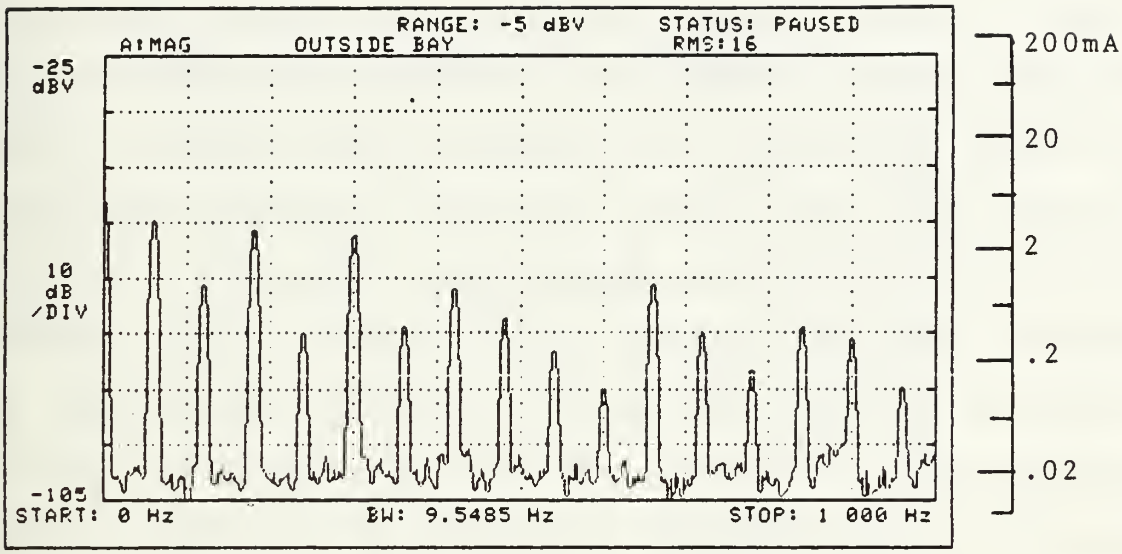
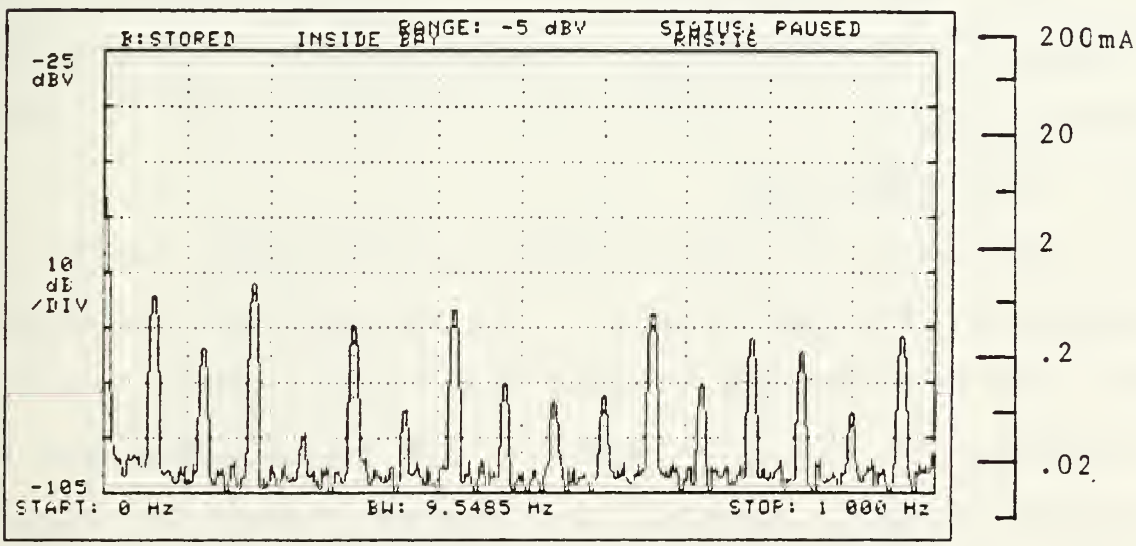


b)

Figure 24. Bay 76 Inside Green Wire Current Green/White Interchanged on Power Supply Cord



a)



b)

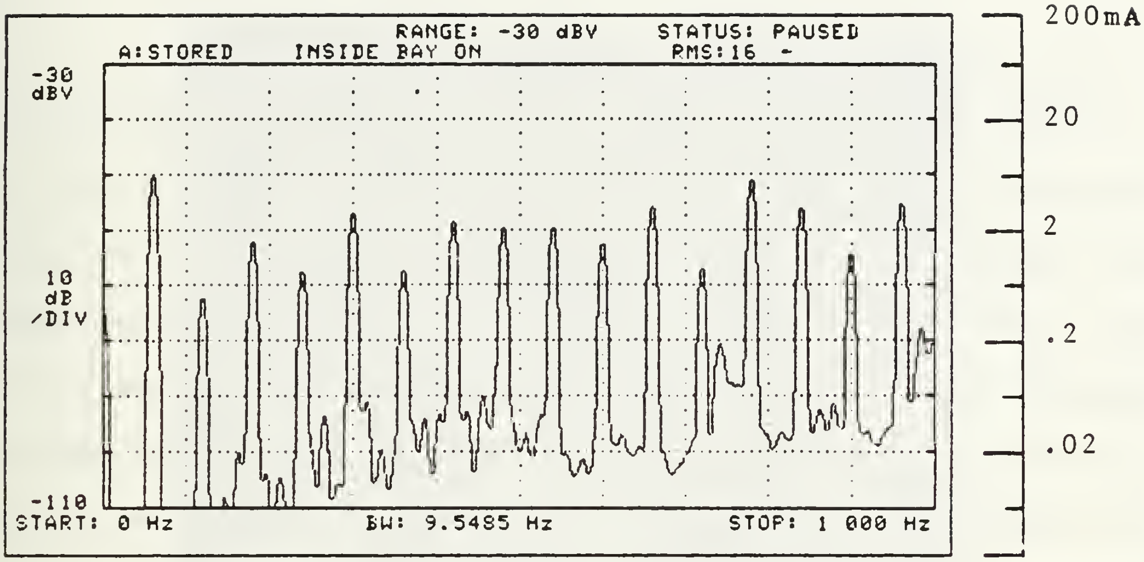
Figure 25. Bay 76 Outside and Inside Green Wire Current Power Supply Cord Removed

internal and external sources of harmonics were equal in magnitude. Since the external sources were associated with building power, they could not be easily controlled. Internal harmonic generation, however, could be controlled by simply turning off all equipment in the cabinet. Figure 26 shows that the internal green-wire currents decreased to very low levels when the equipment was turned off. External harmonic currents remained about the same. Thus, excellent isolation between external and internal green-wires was achieved even though the simplistic measurement did not show isolation. The residual green-wire current shown in the bottom view of Figure 26 was probably conducted into the cabinet by coaxial cable shield currents.

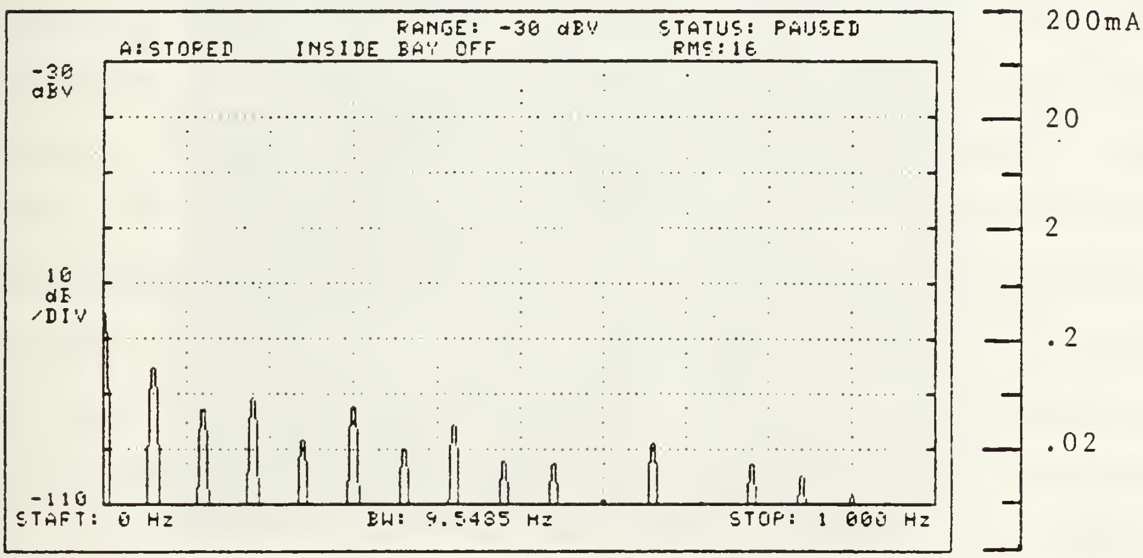
All other measurements of green-wire currents in the equipment cabinets at NSGA Northwest provided indications of good isolation.

C. NSGA SABANA SECA

Barrier plates were added to the cabinets in the RFD system at NSGA Sabana Seca. This installation was similar to that at Northwest in that the barrier plates provided isolation for the green wires of the power cables and for cabinet grounds. External and internal green-wire currents were measured for all modified cabinets. Where mechanically feasible, internal and external ground currents were also



a)



b)

Figure 26. Bay 54 Inside Green Wire Current Equipment On and Equipment Off

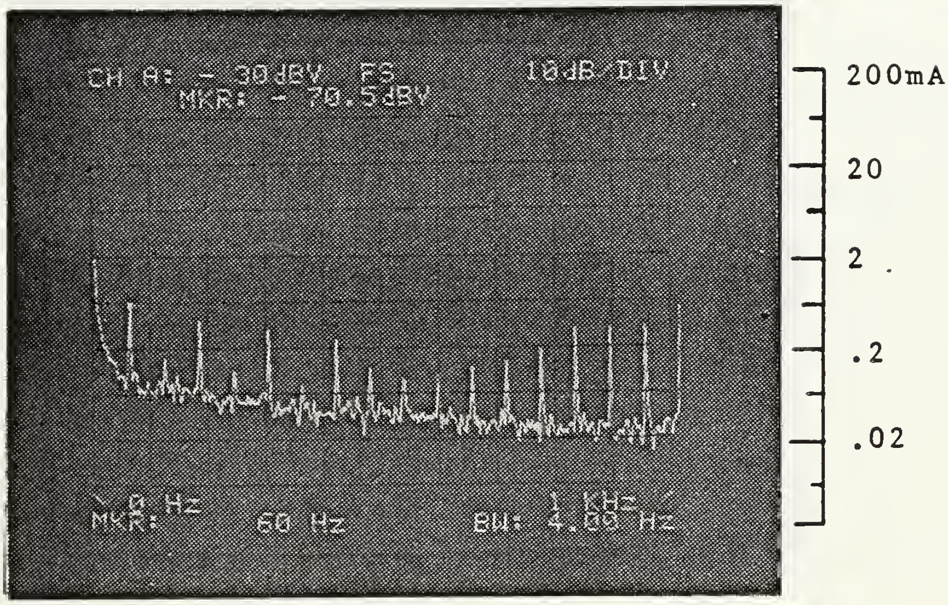
measured. Representative examples of green-wire current results are given in this section.

1. <u>Site Results</u>

Figure 27 shows the inside and outside green-wire currents of a typical multicoupler bay in the RFD room at NSGA Sabana Seca. The data show that about 20 db isolation was obtained from inside to outside. Since the measurement compares the level of externally generated harmonics to the lower level of internally generated harmonics, the data do not provide the maximum value of isolation achieved by the barrier plate.

Figure 28 shows a unique case with lower than normal difference between the inside and outside current levels. This bay houses the FRM-19 test set which has a much higher load then neighboring multicoupler cabinets. In addition, the cabinet contains a line voltage regulator with produces significant levels of harmonics. The outside 60-Hz green-wire current is lower than that of the inside, demonstrating that isolation was achieved. The internal and external harmonic levels are about equal in amplitude, indicating the harmonic sources about equal in amplitude existed both inside and outside the cabinet.

Table 1 tabulates the green-wire currents for both inside and outside the equipment cabinets in the RFD room



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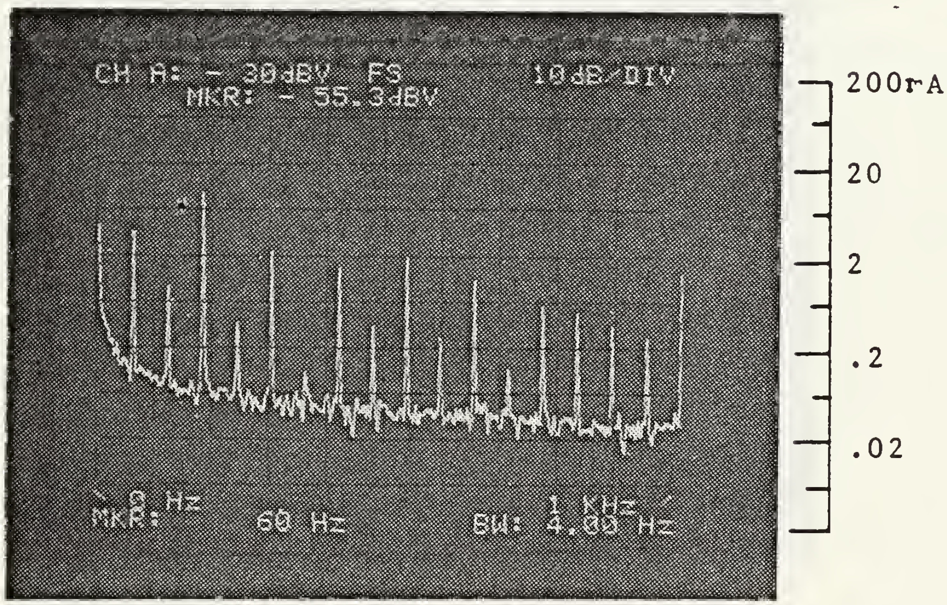
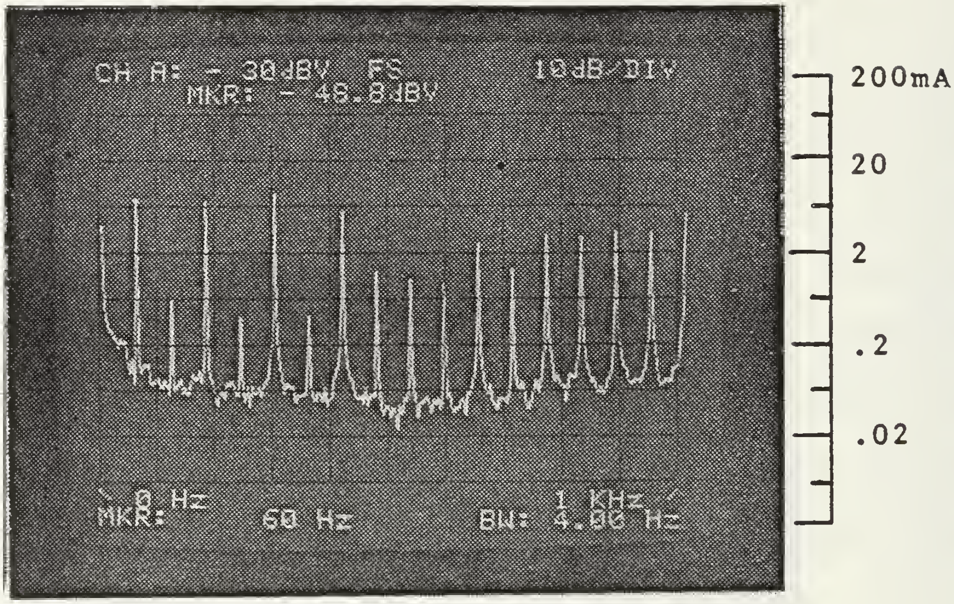
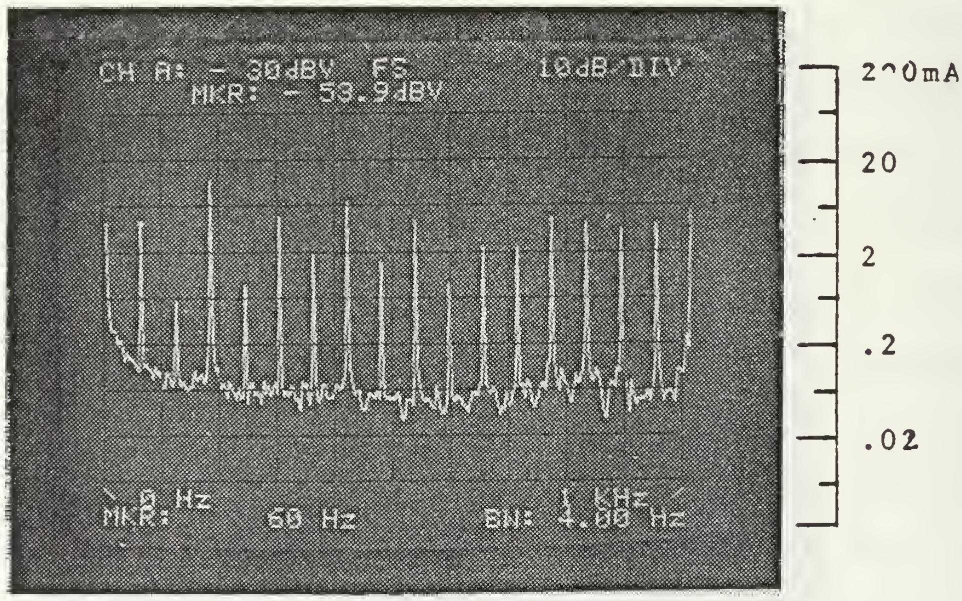


b)

Figure 27. Inside and Outside Green Wire Current RFD NSGA Sabana Seca



a)



b)

Figure 28. Inside and Outside Green Wire Current RFD FRM-19 Sabana Seca

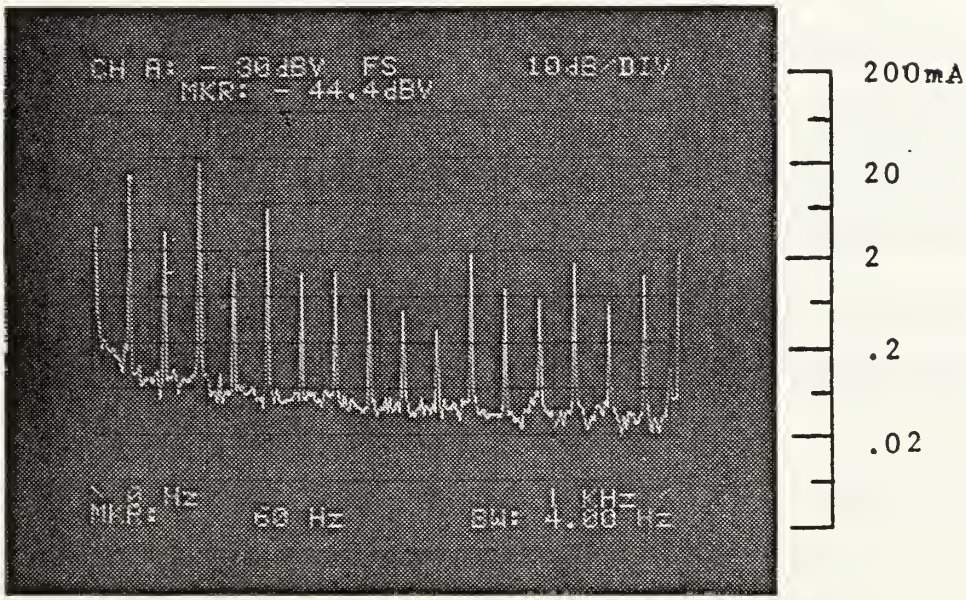
	60 Hz		180 Hz		10KHz	
Bay	Outside	Inside	Outside	Inside	Outside	Inside
1	-53.2	-58.6	-42.2	-58.0	-82.0	-85.0
2	-62.0	-56.5	-54.3	-58.5	-84.0	-83.0
3	-46.0	-57.0	-45.2	-65.1	-82.0	-85.0
4	-45.0	-71.2	-50.1	-61.0	-84.0	-90.0
5	-60.0	-72.9	-50.7	-69.4	-87.5	-87.0
6	-56.5	-65.1	-58.7	-65.6	-86.7	-85.0
8	-58.1	-59.1	-46.4	-57.9	-82.0	-82.8
9	-46.7	-58.2	-47.0	-58.1	-80.0	-81.0
10	-55.3	-70.6	-46.2	-74.4	-84.0	-87.0
11	-57.4	-58.3	-50.3	-65.7	-82.0	-84.0
12	-57.5	-66.3	-57.7	-68.5	-85.0	-84.0
13	-47.4	-68.1	-43.7	-60.0	-85.0	-82.0
14	-52.4	-73.6	-39.0	-65.5	-85.0	-90.0
15	-55.6	-87.4	-41.0	-71.2	-87.0	-94.0
17	-45.5	-66.4	-54.3	-74.6	-73.0	-85.5
18	-51.8	-68.1	-44.9	-60.0	-86.0	-86.0
19	-46.5	-68.7	-43.6	-62.4	-84.0	-88.0
20	-56.8	-63.5	-55.6	-58.8	-86.0	-87.0
21	-48.9	-78.8	-59.3	-63.2	-85.0	-92.0
33	-34.6	-38.2	-43.2	-58.9	-75.0	-77.0
34	-38.0	-35.9	-49.0	-52.9	-72.5	-68.0

TABLE 1
NSGA Sabana Seca RF Distribution Room green wire modifications (all measurements in dbv)

for representative cabinets that had the barrier kit installed. Current levels at 60 Hz, 180 Hz and 10 KHz are provided. The difference between inside and outside current levels indicate that isolation was achieved.

Nearly half of these equipment bays show about 20 dB of difference between the inside and outside green-wire current at 60 Hz. Bays 2 and 34 show the increased internal current because of the presence of a strong harmonic source inside the cabinet.

The bottom view in Figure 29 shows the outside barrier plate installation on one of the receiver positions in the Ullman room. No external 60-Hz or harmonic current were found. Normal internal green-wire currents were obtained (see the top view). Further investigation revealed that fourteen green safety wires in the Ullman room had not been connected at the power distribution panel. Although this may have kept ground interference currents from penetrating the receiver cabinet, it also was a major violation of the National Electrical Code (NEC) for equipment and personnel safety. When the green wires were connected to the power panel, normal ground currents were obtained.



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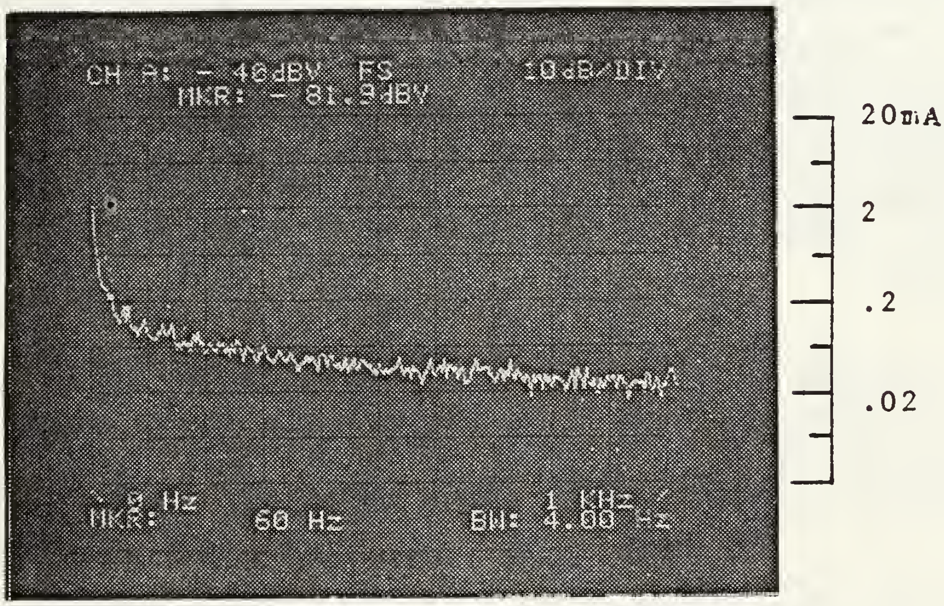

b)

Figure 29. Inside and Outside Green Wire Current Ullman Room Console NSGA Sabana Seca

V. CONCLUSION

The control of radio interference generated within a receiving site has been addressed in this thesis. Emphasis was given to the use of barrier control of interference at the equipment level. Laboratory and field measurements were made to define the amount of isolation provided by the conducting skin of a standard commercial equipment cabinet. The study and measurements provide a number of interesting and useful results. These are summarized as follows:

o Barrier techiques were shown to provide a means to effectively control and limit radio noise conducted into and out of equipment cabinets over power wires, ground conductors, coaxial cable shields, and other conductors that must penetrate the metallic walls of equipment cabinets.

o Barrier control is based on the simple concept of controlling the flow of current produced by sources of interference. Sources of interference external to a cabinet are provided with a current return path back to the sources without penetrating the cabinet walls. Sources of interference within a cabinet are provided a return current path back to the sources without penetrating the cabinet walls.

o Barrier control techniques are especially useful in minimizing the impact of site-generated radio interference to receivers in existing sites. It is recommended that all new equipment installations, and all equipment and facility modernization and modification work be made in accord with barrier control principles.

o The successful implementation of barrier control at the cabinet level depends on the proper use of barrier control on each penetrating conductor that carries, or can potentially carry, radio interference into, or out of, a cabinet. The thesis describes methods of controlling interference entering and leaving cabinets over grounds, power wires, and coaxial shields.

- Significant levels of interference control were obtained using standard inexpensive commercial equipment cabinets.

- Of special importance is the method of cabinet grounding. An external cabinet ground conductor should not directly penetrate a cabinet wall. It should be attached to the external surface of a cabinet. An internal cabinet ground bus must be attached to the internal surface of the cabinet. The green-wire ground of the power conductor must also be connected in accord with barrier control.

- Standard coaxial bulkhead connectors must be used at the cabinet wall for all penetrating coaxial cables that carry, or might potentially carry, radio interference current.

- Power-line filters must be installed at a cabinet wall in conjunction with a barrier. These filters must provide a path for the flow of internally generated noise current, and externally generated noise current, directly to their sources without penetrating a cabinet wall.

- The test power line filter, while not a perfected design, showed a substantial reduction in conducted ambient RF noise current to or from a standard equipment cabinet.

- Barrier principles can also be applied to shielded rooms, equipment rooms, and entire buildings. Multiple barriers will provide additional and additive interference control. These aspects of the control of interference by barrier techniques were not explored in this thesis.

APPENDIX

Measurement Parameters

The following is a list of measurement parameters for all figures used in this thesis. All follow the following format:

Figure 00
Time, Date
Location, Room, Bay
Center Frequency, Span, Bandwidth, Time Span
Probe Setting, Line Amp, Input Attenuation, Reference

Figure 6
1035, 20 Aug 87
NPS, SP219 Lab, Experimental rack
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
P6021(2:1), +40 dB

Figure 7
1120, 20 Aug 87
NPS SP210 Lab, Experimental rack
500 Hz, 1 KHz, 9.5485 Hz, RMS10
P6021(2:1), +40 dB

Figure 8
1515, 23 Oct 87
NPS, SP219 Lab, Experimental rack
2.5 MHz, 5 MHz, 30 KHz
CT5(10:1), 2:1, +31 dB, 0, -20 dB

Figure 11
1150, 28 Oct 87
NPS, SP219 Lab, Experimental rack
2.5 MHz, 5 MHz, 30 KHz
CT5(10:1), 2:1, +20 dB, 0, -20 dB

Figure 12
1200, 28 Oct 87
NPS, SP219 Lab, Experimental rack
2.5 MHz, 5 MHz, 30 KHz
CT5(10:1), 2:1, +20 dB, 0, -20 dB

Figure 13
1215, 28 Oct 87
NPS, SP219 Lab, Experimental rack
2.5 MHZ, 5 MHz, 30 KHz
CT5(10:1), 2:1, +20 dB, 0, -20 dB

Figure 14
1200, 2 Sep 87
NPS, SP219 Lab, experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
P6021(2:1), +20 dB, 0, -20 dB

Figure 15
1242, 2 Sep 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
P6021(2:1), +20 dB, 0, -20 dB

Figure 16
1313, 2 Sep 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
P6021(2:1), +20 dB, 0, -20 dB

Figure 17
1325, Sep 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
P6021(2:1), +20 dB, 0, -20 dB

Figure 18
1444, 21 Oct 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
CT5(20:1), 2:1, +11 dB, 0, -20 dB

Figure 19
1430, 23 Oct 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
Fairchild PCL10, +20 dB, 0, -20 dB

Figure 20
1145, 21 Oct 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
CT5(20:1), 2:1, +11 dB, 0, -20 dB

Figure 21
1045, 24 Nov 87
NPS, SP219 Lab, Experimental rack
10 MHz, 20 MHz, 100 KHz, 100 msec
CT5(20:1), 2:1, +20 dB, 0, -20 dB

Figure 22
1100, 21 Sep 87
NSGA NW, RFD, Bay 34
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
CT5(20:1), 10:1, +40dB

Figure 23
1130, 21 Sep 87
NSGA NW, RFD, Bay 77
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
CT5(20:1),10:1, +40 dB

Figure 24
1410, 22 Sep 87
NSGA NW, RFD, Bay 76
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
CT5(20:1), 10:1, +20 dB

Figure 25
1500, 22 Sep 87
NSGA NW, RFD, Bay 76
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
CT5(20:1), 10:1, +40 dB

Figure 26
1530, 22 Sep 87
NSGA NW, RFD, Bay 54
500 Hz, 1 KHz, 9.5485 Hz, RMS:10
CT5(20:1), 10:1, +40 dB

Figure 27
1415, 28 July 87
NSGA SS, RFD, Bay 10
500 Hz, 1 KHz, 4 Hz, RMS:10
CT5(20:1), 10:1, +40 dB

Figure 28
1615, 29 July 87
NSGA SS, RFD, FRM-19
500 Hz, 1 KHz, 4 Hz, RMS:10
CT5(20:1), 10:1, +40 dB

Figure 29
1040, 27 July 87
NSGA SS, Ullman, Console 4
500 Hz, 1 KHz, 4 Hz, RMS:10
CT5(20:1), 10:1, +40 dB

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